BRITISH WELDING * RESEARCH ASSOCIATION

VOL. 4. JUNE, 1950 No. 3

WELDING RESEARCH

PRICE FIVE SHILLINGS

Published by
THE BRITISH WELDING RESEARCH ASSOCIATION · 29 PARK CRESCENT · LONDON · W.1

Welding Research

VOL. 4 JUNE 1950 No. 3

Published by
THE
BRITISH WELDING RESEARCH ASSOCIATION
Head Office and Metallurgical Laboratory
29 Park Crescent, London, W.1
Telephone, Langham 7485
Telegrams, Weldaserch, Wesdo, London.

Research Station
Abington Hall, Cambridge
Telephone, Linton 375
Telegrams, Weldaserch, Cambridge

Director of Research, H. G. Taylor, D.Sc.(Eng.), D.I.C., M.I.E.E., F.Inst.P.
Secretary, N. A. W. Le Grand.

Contents

	Page
Association Notes	39r
Recommendations for the Metal-Arc Welding of Butt Welds in Steel Pipelines for Power Plant	40r
The A.C. Argon Arc Process for Welding Aluminium. The Oscillographic Analysis of the Application of a Commercial High Frequency Spark Injector Unit	47r

Association Notes

Recommendations for the Metal-Arc Welding of Butt Welds in Steel Pipelines for Power Plant

The recommendations cover the butt welding, by the metal-arc process, of steel pipelines of wall thickness from 8 s.w.g. and of diameters exceeding 2 in. O.D. By the methods recommended, pipelines varying from these limits up to 13 in. O.D. and wall thicknesses reaching 1¼ in. have been successfully constructed for working pressures up to 2000 lb. per sq. in. and working temperatures of 540 deg. C. (1000 deg. F.). The parent materials considered include mild and medium carbon steels; molybdenum, chrome-molybdenum, and molybdenum-vanadium alloy steels to certain defined specifications.

The A.C. Argon Arc Process for Welding Aluminium The Oscillographic Analysis of the Application of a Commercial High Frequency Spark Injector Unit.

In this report results are given of applying electromagnetic and cathode ray oscillographic recording techniques to the study of certain electrical parameters in the a.c. Argon arc process for welding aluminium. The nature of the output from a commercial high frequency spark oscillator unit such as commonly used in practice is considered here in relation to its application to this process.

The output from such a unit is not continuous but consists of "grouped series" of sparks separated by "dead" periods in which sparks are absent. It is shown both experimentally and also from a consideration of the nature of this output, that it is a matter of considerable importance to the success of the welding process, that these injected spark groups should be correctly phased relative to the main welding current, i.e., that correct phase adjustment should be made between the input supplies to the high frequency spark unit and the welding transformer.

The time durations of the phenomena involved were of the order of a microsecond for individual sparks, a millisecond for the interval between individual sparks, 6 milliseconds for the spark groups and 4 milliseconds for the "dead" period between successive spark groups. From a study of the oscillographic data together with the corresponding weld test runs, it was found that the optimum relative phasing for successful welding was such that the middle of the spark group occurred just after the welding current reached zero.

Correct phasing eliminated half cycle rectification when working to a work piece of an Al-5%Mg alloy, at an open circuit welding voltage of 60V r.m.s. Change of the relative position results in variation in the time delays to arc re-ignition in half-cycles of reverse polarity (work piece negative). Such delays had a marked influence on current asymmetry, quite apart from the asymmetry which is normally present in the tungsten-aluminium arc unless special steps are taken for its prevention. In these investigations the reverse polarity current decreased by some 30 per cent. per millisecond delay from the instant of current zero to the arc re-ignition.

Effects are also noted consequent on changing the work plate material from an Al-5%Mg alloy to commercially pure aluminium, whilst the surface condition of the former was also found to influence results. The differences in behaviour were reflected in the oscillograms.

Some attention is also given to operational adjustments to the spark injector unit, bearing on its efficiency in promoting satisfactory welding; whilst a simple switching method is described for obtaining optimum phasing of the inputs to the high frequency spark injector unit and the welding transformer, for satisfactory welding.

New Members

The following new Members have been elected:—

Bayliss, Jones & Bayliss Ltd.
British Electricity Authority
British Messier Ltd.
Elliott Bros. (London) Ltd.
Husband & Co.
Mathew Hall & Co. Ltd.
National Coal Board
The Projectile and Engineering Co. Ltd.
Thomas Hedley & Co.
Welding Rods Ltd.

Annual General Meeting

The Fifth Annual General Meeting of the Association is to be held at the Research Station, Abington, near Cambridge, on the 13th July, 1950.

R.57

Recommendations for the Metal Arc Welding of Butt Welds in Steel Pipelines for Power Plant

1. FOREWORD

The successful welding of circumferential butt joints in pressure pipelines by the metal-arc process necessitates special techniques in order to achieve consistent and satisfactory penetration without either the formation of cracks at the base of the welds or the formation of icicles protruding into the bore of the pipe.

As a means of giving consistent penetration and root fusion, two main methods are available. The first method involves the use of a backing-ring which may be retained as part of the final joint or may be removable, and the second method involves the use of a base run of weld metal deposited by the oxy-acetylene process.

The methods given in this memorandum are the best generally available at the present time, but there are indications that the adoption of special techniques or specially trained workmen may enable backing-rings or oxy-acetylene base runs to be dispensed with. Any such proposal should be very carefully investigated to verify that welds made in all positions will pass consistently the test requirements of this memorandum.

2. SCOPE

These recommendations are applicable to butt welds in pipelines of wall thicknesses from 8 s.w.g. and of diameters exceeding 2 in. outside diameter. By the methods recommended, pipelines varying from these limits up to 13-in. outside diameter and wall thicknesses reaching 1¼ in. have been successfully constructed for working pressures up to 2000 lb. per sq. in. and working temperatures of 540° C. (1000° F.). Butt welds in piping of similar sizes and for similar conditions have also been constructed by the oxy-acetylene process throughout (see Memorandum T.5).*

The oxy-acetylene process generally will be found more suitable for the smaller pipes up to approximately 4 in. outside diameter and ¼ in. wall thickness. Above these sizes and thicknesses, oxy-acetylene welding becomes tiring and uncomfortable for the welder owing to the large amount of heated metal, and it is recommended that metal-arc welding be used to the limit of its capabilities.

3. PARENT METAL

The parent metal may be wrought or cast material of the following types:—

(a) Mild steels conforming to the requirements of B.S.S. 806 for the duty of the pipeline being welded, or mild cast steel to Grade (i) of B.S.S. 592, with a maximum carbon content of 0·25 per cent.

(b) Mild steels of 0·25-0·3 per cent. carbon content. Medium carbon steel with a maximum carbon content of 0·4 per cent.

(c) Molybdenum steel with a molybdenum content of 0·4-0·6 per cent. and a carbon content not exceeding 0·3 per cent.

(d) Chrome-molybdenum steel with a chromium content not exceeding 1·5 per cent., molybdenum content not exceeding 0·6 per cent. and carbon content not exceeding 0·25 per cent.

(e) Molybdenum-vanadium steel with a molybdenum content of 0·5-0·6 per cent., vanadium 0·25-0·3 per cent. maximum, and a carbon content of 0·12 per cent. maximum. Experience in this class of steel is somewhat limited, and for the time being it is recommended that a rather more exhaustive series of tests should be made on typical pipe welds before commencing production.

* These recommendations are based on the manufacture of many pipelines for a variety of service conditions, together with large numbers of tests on joints, carried out by members of the FE.10 Committee.

4. WELDING METHODS

Welding may be carried out by any of the following methods:—

(A) Metal-arc welding with a permanent steel backing-ring which may be either of mild steel or of the same composition as the pipe.

(B) Metal-arc welding with a base run deposited by the oxy-acetylene process.

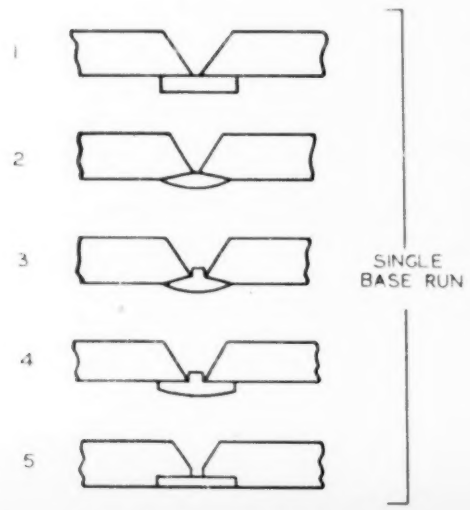
(C) Metal-arc welding with a steel backing-ring that can be removed when welding is completed.

(D) Metal-arc welding where conditions of access allow an internal run at the root of the weld.

Methods (C) and (D) are particularly applicable to the welding of long-neck flanges.

(A) Metal-Arc Welding with Permanent Internal Backing-Ring

(i) *Form of Backing-ring.* Backing-rings of the forms shown in Figs. 1-11 have been prepared for this method of welding. Plain rectangular rings of the type shown in Fig. 1, with the maximum projection into the bore, are not suitable as they interpose an increased resistance to flow. Backing-rings fitting tightly into machined recesses with square or sharp corners, or of such a shape as to restrict longitudinal contraction (Figs. 2-5), are not to be

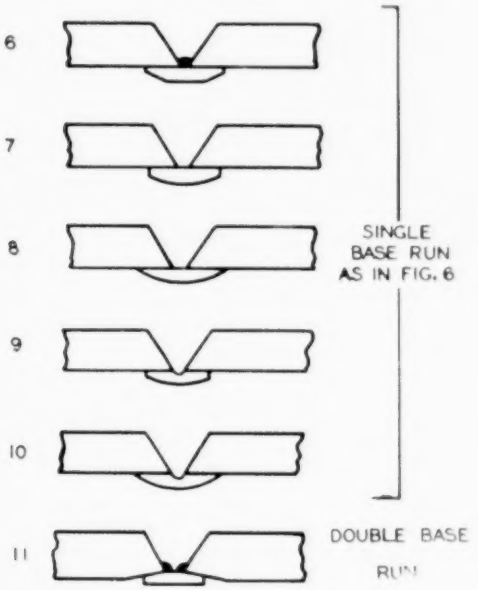


Figs. 1-5. Types of backing ring not recommended.

generally recommended as they increase the tendency to basal crack formation unless a sufficiently wide gap is adopted to allow of two base runs.

Recommended types of backing-rings are shown in Figs. 6-10; those with a central groove are suitable for pipes over 6 in. bore. A ring of the form shown in Fig. 11 may also be recommended providing the gap is wide enough to enable two base runs to be laid as shown.

The backing-ring should fit closely to the bore of the pipe all round, and to achieve this, the pipe should be internally machined



Figs. 6-11. Recommended backing rings.

or sized as described under Clause (iii) *(a)*. Backing-rings may be rolled from strip to the circumferential form, or may be machined from pipes of suitable dimensions. A good fit may be achieved with a machined ring by a split in the ring to allow the ring to spring into the pipe. The gap between the ends of the fitted ring should not exceed $\frac{1}{4}$ in.

Backing-rings should be made from mild steel with a sulphur content not exceeding 0·06 per cent. maximum, since a high or segregated sulphur content of the backing-ring may produce defects at the base of the weld. Backing-rings, if desired, may be of the same material as the pipe.

Copper backing-rings have been used, but are not recommended owing to the danger of pick-up of copper by the weld metal.

(ii) *Tacking of Backing-rings.*—To prevent dislodgment of the backing-ring during erection of the piping, the backing-ring may, if desired, be tack welded at intervals or continuously round the bore of the pipe (see Fig. 12).

(iii) *Preparation of Pipe Bends.*

*(a) Sizing of Pipes.**—The bores at the ends of adjacent pipes

* In the case of ordinary Bessemer steel piping, the expansion or drifting by cold expansion should be restricted to a maximum of 1 per cent. of the pipe diameter.

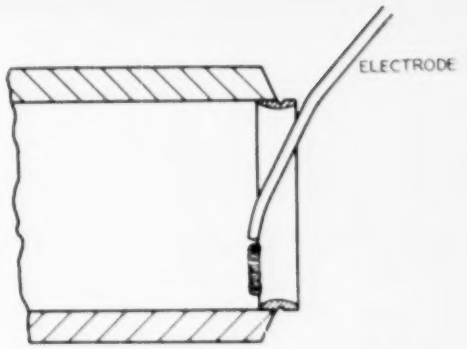


Fig. 12.—Method of tacking in backing ring.

should match and the clearance between the backing-ring and the bores should not be more than $\frac{1}{32}$ in., preferably less, at any point. It is recommended that where practicable the sizing and rounding of the pipe ends be carried out by machining.

For pipes up to $\frac{1}{2}$ in. wall thickness, the bores can readily be made circular and sized by expanding or drifting without subsequent machining, by cold expansion to not more than 3 per cent. of the diameter, and by hot expansion where the diameter is to be increased more than 3 per cent. In the case of the molybdenum, chrome molybdenum and molybdenum vanadium steels, the temperature of the metal should not exceed 650 deg. C., the temperature being checked by a suitable pyrometer.

Pipes with wall thicknesses greater than $\frac{1}{2}$ in. may be sized by machining the internal surface. At no point on the circumference should the wall thickness be reduced appreciably below the minimum wall thickness of the pipeline. Some slight reductions in wall thickness may be permitted if care is taken to ensure that the weld reinforcement adequately compensates for such occurrences.

Where machining of the smaller of two adjoining pipes would reduce the final wall thickness appreciably below the allowable minimum, the smaller bore pipe should first be drifted or expanded before finally machining.

In the case of cylindrical backing-rings, the bore should be parallel and truly circular for a distance of half the width of the backing-ring plus $\frac{1}{4}$ in. from the pipe end, the parallel portion to run out at an angle of less than 5 deg. to meet the inner pipe wall (see Fig. 13). In the case of taper backing-rings, the machined taper should run out directly into the pipe bore at an angle not greater than 10 deg. The sizing and machining of the bores should be carried out before bevelling the pipe ends.

(b) Bevelling of Pipe Ends.—Table I gives recommended preparations for bevelling of the ends of pipes.

The form of groove may be a plain vee with a root face

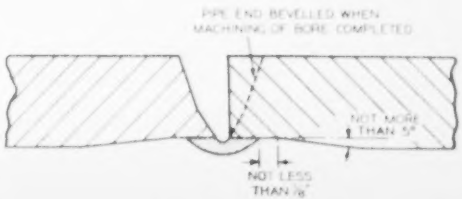


Fig. 13.—Details of pipe ends showing machining of bore.

Table I

Wall thickness	Root Face	Gap	Weld Groove
Less than $\frac{1}{4}$"	Not more than $\frac{1}{16}$"	$\frac{1}{16}$" minimum	Plain vee (Fig. 14)
$\frac{1}{4}$" and over	Not more than $\frac{1}{16}$"	$\frac{1}{16}$" minimum	Plain vee (Fig. 14). Dougle-angle vee (Fig. 15). U-groove (Fig. 16)
$\frac{1}{2}$" and over using taper backing-ring	$\frac{1}{16}$"	$\frac{1}{16}$" minimum	Plain vee (Fig. 11 and Fig. 17)

(Fig. 14) a vee with double-angle (Fig. 15) and a U with lips at the base (Fig. 16).

To facilitate welding of vertical pipes, the angle of bevel may be varied if desired in any particular case to give a larger angle at the end of the upper pipe than at the lower pipe, as shown in Fig. 18.

(iv) *Preheating.*—Preheating is desirable according to the dimensions and type of material of the pipes. The recommendations are given in Table II.

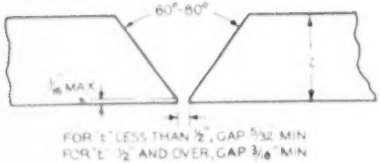


Fig. 14.—Plain Vee for use with backing ring (all thicknesses of piping).

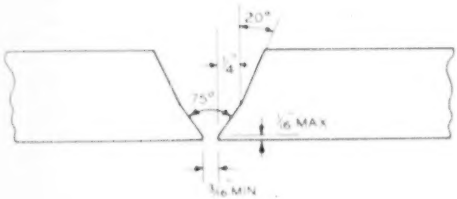


Fig. 15.—Double angle vee for use with backing ring (pipes over $\frac{1}{4}$ in. thick).

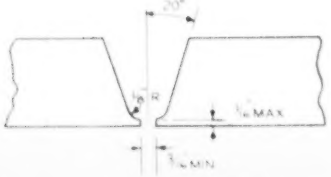


Fig. 16.—U-groove for use with backing ring (pipes over $\frac{1}{4}$ in. wall thickness).

Table II

Parent Metal	Thickness	Temp. for Preheat
(*a*) Mild steel : up to 0·25 per cent. C Mild steel : over 0·25 per cent. C	Up to $\frac{1}{2}$" Over $\frac{1}{2}$"	*Optional 200° C. minimum
(*b*) Mild steel, 0·25-0·3 per cent. C Medium carbon steel up to 0·4 per cent. C	All thicknesses	200° C. minimum
(*c*) Molybdenum steel Molybdenum steel	Up to $\frac{1}{2}$" Over $\frac{1}{2}$"	*Optional 250° C. minimum
(*d*) Chrome-molybdenum steel	All thicknesses	250° C. minimum
(*e*) Molybdenum-vanadium steel	All thicknesses	280° C. minimum

* In very cold weather, a minimum temperature of 50° C. should be adopted.

(*a*) *Method of Preheating.*—Preheating may be carried out by:—

(1) Gas rings or muffle furnaces.

(2) Electric resistance preheaters.

(3) Induction heating.

(4) Oxy-acetylene or other gas torches.

The choice of method is dependent on local conditions. So long as the equipment maintains satisfactory temperature distribution and does not interfere with the welding operation, all these methods are acceptable, but it must be noted that method (4) involving the use of gas torches should be restricted to pipes up to approximately 4 in. bore, as on the larger diameters uniformity of temperature is too difficult to achieve.

(*b*) *Temperature Measurement.*—The temperature of preheat should be determined by a base-metal thermocouple welded or securely attached to one of the pipes. For horizontal pipes, the thermocouple should not be more than 2 in.-2½ in. from the groove at one or both sides of the joint. For vertical pipes, the thermocouple should be at the lower of the two pipes, not more than 2 in.-2½ in. from the edge of the groove preparation. Temperature-indicating paints or crayons may be used, bearing in mind that there may be a time lag and that one paint or crayon will not indicate how much the minimum temperature is exceeded, and some types of crayons will not show, once the temperature has been reached, that this temperature is not being maintained. In these cases, the paint or crayon has to be re-applied if continued temperature observations are to be made.

(v) *Electrodes.*—It is recommended that only those coated electrodes should be used which have been found by experiment to deposit weld metal of the quality necessary to meet the test requirements specified later.

For the molybdenum and chrome-molybdenum steels an electrode depositing weld metal containing 0·4-0·6 per cent. molybdenum should be used. In some cases it is not essential that the electrode should contain chromium when welding the chrome-molybdenum steels. As a further safeguard against basal crack formation on these alloy steels, it is sometimes found advantageous to deposit the first run using good-quality mild steel electrodes.

(vi) *Sizes of Electrodes and Amperages.*

The size of electrode and current to be employed for all but the first run is governed by two factors:—

(*a*) The skill of the welder in controlling the electrode performance. (For positional welding the greater the skill the larger the size of electrode that can be controlled.)

Table III

Run	Size	Current
First run	10 s.w.g. or $\frac{1}{8}$" diameter	90-120 amps.
Subsequent runs	10 " " $\frac{1}{8}$" "	90-120 "
	8 " " $\frac{5}{32}$" "	140-175 "
	6 " " $\frac{3}{16}$" "	160-250 "
	4 " " $\frac{1}{4}$" "	240-350 "
	2 " " $\frac{5}{16}$" "	300-450 "

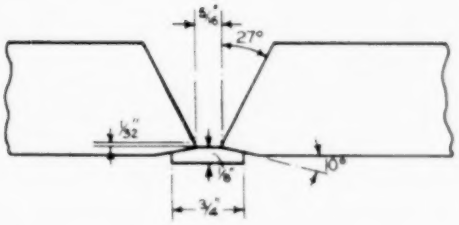


Fig. 17. Preparation of groove for use with taper backing ring (pipes over $\frac{1}{2}$ in. wall thickness).

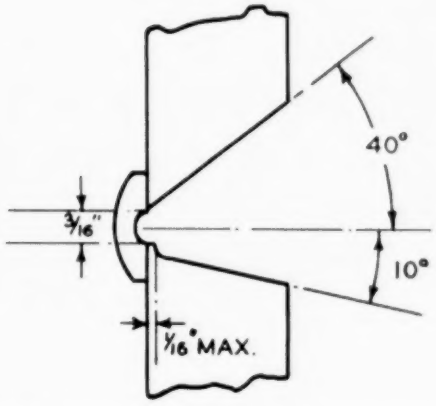


Fig. 18. Joint preparation for vertical pipes, using backing ring.

(*b*) The position of the pipes. (For heavy-wall pipes that can be rotated, the largest gauge of electrode specified can readily be used.)

(vii) *Welding Technique*.—The deposition of weld metal on the backing-ring at the base of the groove may be made in one run, as in Fig. 6-10. The technique of forming the base weld in two runs, as given in Fig. 11, is permissible when the joint design has been specifically prepared for this technique. The base run or runs should be carried out with little or no weaving of the electrode.

For site welding on horizontal pipes, where a single base run is used, the vertical-upwards method is recommended; where the base run is formed in two runs, these may be made either by the vertical-upwards or vertical-downwards method. In each case, the second layer may be made vertical-downwards if desired. For bench or shop welding, where the pipe may with advantage be rotated during welding, all welding is carried out in the downhand position.

After depositing the base run or runs, in the case of horizontal pipes and pipes inclined at an angle up to 45 deg. to the vertical the remainder of the joint should generally be welded by weaving the electrode from side to side across the weld groove, using the vertical-upwards method. For vertical pipes and pipes sloping at an angle greater than 45 deg., the bead technique is preferable, the runs of weld metal overlapping each other in proper sequence, care being taken to avoid stringers of trapped slag and undercutting at the top edge of the weld (see Fig. 19).

"Dabbing" of the electrode on the pipe wall to remove slag from the tip or to start the arc, must not be practised. A piece of scrap plate clamped to the pipe near the weld groove should be used for this purpose.

(viii) *Cleaning and Removal of Slag, Peening and Chipping of Weld Metal*.—All slag must be removed after each run. This may be carried out conveniently with a pneumatic or manual chipping tool. Each layer of weld metal may be peened, but this is not necessary with a good welding technique. Undercut edges, slag pockets, unsound metal and blowholes should be chipped out before further weld metal is deposited.

The quality of a pipe weld depends very largely on the care given to these operations, undercut edges leading to slag stringers being the most common source of trouble.

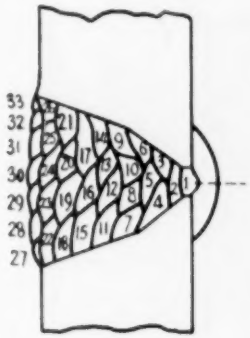


Fig. 19. Suggested sequence of beads in vertical joint.

(B) Metal-Arc Welding with a Base Run Deposited by the Oxy-Acetylene Process

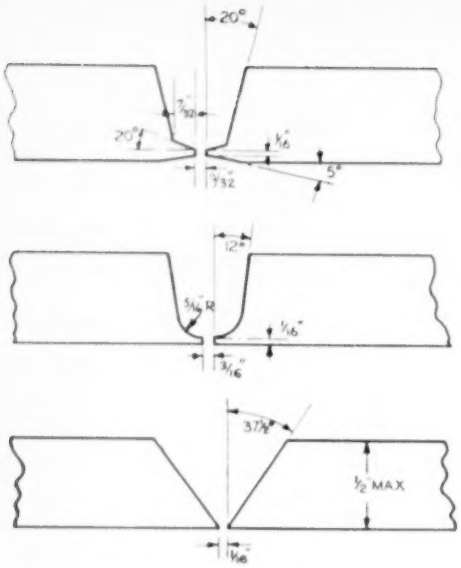
No object is served by using this method of welding on pipes with a wall thickness less than $\frac{1}{4}$ in., since oxy-acetylene welding throughout is entirely satisfactory.

Pipe ends should be sized in accordance with the recommendations given under "Sizing of Pipes" Section (A) (iii).

(i) *Bevelling of Pipe Ends*.—Figs. 20, 21 and 22 give three preparations of pipe ends for this method of welding. The plain vee of Fig. 22 has been used but it is not recommended for pipe thicknesses over $\frac{1}{2}$ in.

(ii) *Preheating*.—For the deposition of the oxy-acetylene base run, the pipe ends should be preheated to 350 deg.-375 deg. C. Temperatures up to 450 deg. C. can be tolerated, but higher temperatures would lead to such discomfort on the part of the welder that the welding quality might easily suffer in consequence. Preheating may be accomplished by any of the methods given in Section (A) (iv) (*a*).

(iii) *Welding Technique*.—The method of welding the base run



Figs. 20-22. Preparation for oxy-acetylene base run.

for positional welds should be the rightward or the all-position rightward technique as described in Technical Memorandum T.5. Where tacking welds are adopted, any such tacking welds should be completely melted out during welding.

(iv) *Characteristics of Base Run.*—The base run should be sufficiently thick to prevent melting or blowing-through of the first run of metal-arc welding. The thickness should consequently be between $\frac{1}{8}$ in. and $\frac{1}{4}$ in. The base run should be given an evenly rippled bead of smooth contour both internally and externally.

(v) *Filler Metal for Base Run.*—A suitable welding rod for the base run is to the specification:

Carbon	0·1-0·15 per cent
Manganese	1·3-1·6 ,,
Silicon	0·1-0·2 ,,
Sulphur	0·04 per cent. max.
Phosphorus	0·04 ,,

A welding rod to this analysis may be used for the molybdenum and chrome-molybdenum steels, but if preferred a welding rod containing approximately 0·5 per cent. molybdenum may be employed. It is not recommended that a chrome-molybdenum steel welding rod be used.

(vi) *Metal-arc Welding on Oxy-acetylene Base Run.*—Subsequent deposition of weld metal by the metal-arc process should be carried out in accordance with the methods set out in Sections (A) (v), (vi), (vii) and (viii). The metal-arc welding should proceed immediately after the oxy-acetylene base run has been completed, without cooling below the minimum preheat temperature required for subsequent metal-arc welding. Preheating should follow the recommendations of Section (A) (iv).

(C) Metal-Arc Welding with a Steel Backing-Ring that can be removed when Welding is Completed

When conditions of access are such that the backing-ring can be removed by machining or chipping and grinding, the recommended backing-ring is as shown in Fig. 23. After welding is carried out in accordance with the recommendations of Method (A), the ring may be removed and the internal surface machined or ground to a smooth contour.

(D) Metal-Arc Welding where Conditions of Access Allow an Internal Run at the Root of the Weld

Where conditions of access render it possible, as in the case of some long-neck flanges, an internal weld or sealing run may be used instead of a backing-ring or of a base run of oxy-acetylene weld metal. The internal weld can be made either before or after welding the main outer groove. In the latter case, it is advisable to

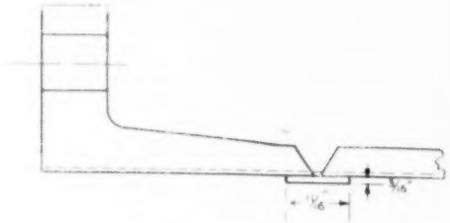


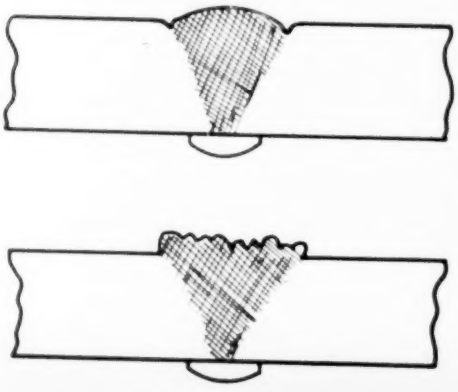
Fig. 23. Backing ring suitable for use with long-neck flanges. Bore machined after completion of welding.

grind, chip or machine out the back of the groove to sound metal, subsequently welding with a sufficiently high current to give good penetration.

5. REINFORCEMENT OF WELDS

Normally, welds are to be reinforced on the external surface, the reinforcement recommended being approximately 20 per cent. of the pipe thickness, with a minimum of $\frac{1}{16}$ in. and a maximum of $\frac{1}{8}$ in. The reinforcement should run out smoothly into the pipe on either side of the weld, with the minimum of undercut or thinning of the pipe at the edge of the weld. (See Figs. 24 and 25.) Where a smooth contour is desirable, the weld surface may be dressed by chipping or grinding.

Where pipes of similar bore but different wall thickness have to be joined, the thicker pipe should either be machined externally to match the thinner pipe so that the maximum taper is not greater than 1 in 4, or the weld reinforcement should be built up to give a similar smooth taper.



Figs. 24-25. Unsatisfactory type of reinforcement.

6. SUPERVISION OF WORKMANSHIP

The welding should be under the control of a competent welding supervisor to ensure that the standard of workmanship is in accordance with these recommendations, and the contracting company should ascertain that the quality of the materials used also complies with these recommendations.

The contractor should take steps to ensure that any welder employed on pipelines is capable of making welds of the type required to fulfil the tests set out in Section (8). It is recommended that such tests should be carried out on sample welds before a welder is considered as being capable of undertaking work of the standard set out in these recommendations. Adequate records of such tests should be retained by the contractor.

Where necessary, welders should be provided with suitable rigid staging and with protection against inclement weather conditions so as to enable them to perform correctly the welding operation.

All welding equipment should be maintained in good condition, and such as to enable the welder to maintain the correct flame when using oxy-acetylene welding, and the correct current during metal-arc welding.

The surfaces to be welded and the adjacent material should be cleaned of scale, rust, paint, oil or other injurious foreign matter.

To maintain the recommended gap and alignment during welding, the pipes to be welded should be securely held in position by mechanical means or by tack welding. In general, where tack welds are employed, such welds should either be chipped away or melted out during welding. Bridge pieces and clamps which are to be tack welded to the pipe for the purpose of alignment should be made from mild steel of not over 0·25 per cent. carbon content, with a maximum sulphur content of 0·06 per cent. Bridge pieces and clamps should not be tack welded to the pipe for the purpose of alignment unless it is intended that the tack welds be subsequently ground off smooth after removal of the clamps.

Where backing-rings are not used, the outsides of the pipe ends may be machined concentric with the bores to facilitate alignment of the bores.

Copper, bronze or brass earthing clips should not be attached to the pipes on account of the danger of copper pick-up by arcing. Special all-steel earthing clamps should be used.

A warning is given against the practice of earthing pipes through roller supports in the case of pipes which are to be rotated during welding. Bad contacts may give rise to alteration in voltage and current at the arc, in addition to the danger of melting spots on the pipe surface due to arcing at the rollers. It is recommended that special all-steel earthing clamps be securely attached to the pipes themselves.

7. HEAT-TREATMENT AFTER WELDING

All joints in pipes over ¾ in. thickness or 6 in. outside diameter should be stress-relieved at 600-650 deg. C. after completion of all welding. The stress-relieving temperature should be maintained for one hour per inch of wall thickness, with a minimum of half-an-hour.

It is recommended that the stress-relieving treatment should be recorded using chromel-alumel or platinum-platinum-rhodium thermocouples. The thermocouples should be peened or welded to the surface of the pipe. The stress-relieving can conveniently be undertaken by means of gas muffle furnaces or induction coils, and thermocouples should be positioned so as to ensure that a band of metal with a minimum width of roughly 4 in. is heated to the required temperature.

In the case of molybdenum-vanadium steels, the heat-treatment recommended by the steel makers is normalising at a temperature of 950-970 deg. C., followed by a tempering treatment at 690 deg. C. for five hours.

Where the effects of thermal expansion in service are counteracted by "cold pull" during erection of a pipeline, it is essential that the "cold pull" be maintained during welding, subsequent heat-treatment and cooling.

8. TESTS FOR QUALITY OF BUTT JOINTS

The removal of joints from welded pipelines, other than quite small-bore piping, for test purposes, is inconvenient. Before commencing a pipeline, however, the contractors should be prepared, if called upon, to make a specimen weld representative of the thickness and diameter of the joints in the pipeline and welded under conditions of equal difficulty.

For pipes up to 3-in. bore, the joint should be cut into four longitudinal segments, pipes over 3 in. and up to 6 in. nominal bore should be cut into eight segments, and for pipes over that diameter the representative weld should be cut into twelve segments. (See Fig. 26.)

(a) Macro-etching and Examination for Basal Cracks.—Half of the test strips should be polished and macro-etched at the weld, and examined carefully for basal cracks.

(b) Bend Tests.—From the remaining strips, direct bends and bend tests with the inner surface of the pipe in tension should be made. The samples should have the backing-ring removed, and the internal and external surfaces ground flush with the internal and external surfaces of the pipe. The sample should then be bent at an angle of 90 deg. round a former, the diameter of which is equal to three times the wall thickness of the pipe. The width of the bend test specimen should be approximately equal to the thickness of the pipe wall. Each of the specimens should bend to 90 deg. without signs of serious failure. Slight premature failure at the edges of the specimen is not to be considered as a cause for rejection. Neither would the opening-up of a slight defect due to lack of penetration or absence of root fusion be considered a cause for rejection, provided the defect has sound metal at the back and on either side (See Fig. 27.)

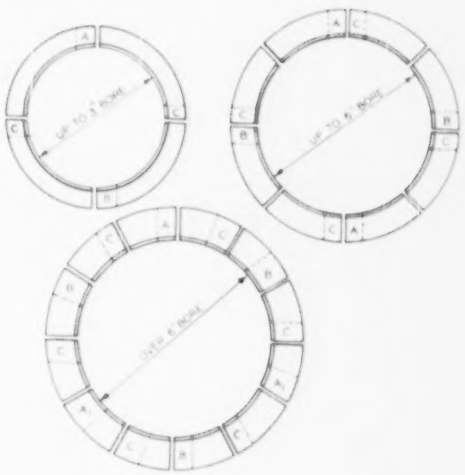


Fig. 26. Sectioning of specimen joints for examination.

Should the tests from the specimen weld prove unsatisfactory, further specimen welds by the same welder should be prepared, until it is proved that the technique is reliable.

(c) Site Examination.—General examination of the welding carried out at site should ensure that slag is adequately removed, that the weld metal is being deposited in a manner satisfactory to

visual observation, that slag is not being trapped at undercut edges, and that obviously unsound metal is not being allowed to remain in the joint.

(ii) *Sampling of Weld Metal.*—If for any purpose it is necessary to obtain a sample of the weld metal from a pipeline, this could be done conveniently by means of a probe-sampler for pipes over ½-in. thick. Two oblique cuts are made equi-distant on either side of the weld metal, triangular in cross-section, containing or not some of the parent metal, as may be desired (see Fig. 28). From such a slice, bend, miniature tensile, macro- and micro-specimens could be prepared. This cut can subsequently be welded up after preheating the joint to the full pre-heating temperature and finally stress-relieving. It must be emphasised that this sampling is only considered essential when a real cause for such action had been established.

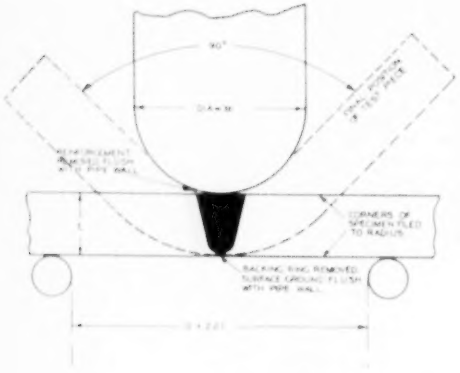


Fig. 27.—Positioning of specimen for bend test.

(iii) *Radiographic Examination.*—One method available for the non-destructive testing of finished welded joints is radiographic examination, either by X- or Gamma-ray.

Much thought must be given before specifying X-ray examination because such examination is costly and there are practical difficulties in carrying it out. Special attention will be necessary to ensure that welds are located in suitable positions for X-ray examination.

Where a hole may be drilled in the pipe wall adjacent to the weld to be examined, Gamma-ray examination, by means of a radio-active source inserted through the hole in the pipe, may prove simpler; this method involves the closure of the small hole.

Some members of the committee express the view that the expense and difficulties of radiographic examination are so great as to rule it out as a practical method of checking and testing. On the other hand, many members of the committee, some of whom regularly practice the radiographic examination of pipe joints, are of the opinion that in certain circumstances there is a strong case for the checking of the quality of pipe butt welds by some form of radiographic examination. Butt welds in high pressure pipelines made by a contractor without previous experience in this field should certainly be checked by radiographic examination. Even with experienced contractors it may be desirable to carry out a certain amount of checking of quality by radiographic examination, where the conditions of service of the pipeline are particularly onerous. When the quality of welding shown by such radiographic examination becomes consistently satisfactory, a reduction can be made; this reduction to be based on experience and by agreement between contractors and purchasers.

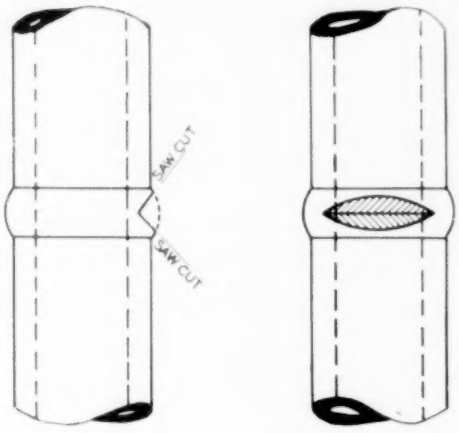


Fig. 28.—Sampling of site weld metal.

Appendix

Hydraulic Test.—Each pipeline may be subjected to a hydraulic test pressure equal to one-and-a-half times the working pressure. Prior to this test, it is advisable to see that the supports are adequate to carry the weight of water during test. If any leaks occur, the defective portion should be completely cut out and rewelded, using pre-heating where necessary, and the weld should be finally stress-relieved and subjected to further hydraulic test. A leak should not be repaired merely by fusion of the surrounding metal.

R.58

The A.C. Argon Arc Process for Welding Aluminium. The Oscillographic Analysis of the Application of a Commercial High Frequency Spark Injector Unit.

By L. H. Orton, Ph.D., F.Inst.P., J. C. Needham, B.Sc.(Eng.), and J. H. Cole, M.Sc.

SUMMARY

In this report results are given of applying electromagnetic and cathode ray oscillographic recording techniques to the study of certain electrical parameters in the a.c. Argon arc process for welding aluminium. The nature of the output from a commercial high frequency spark oscillator unit such as is commonly used in practice is considered here in relation to its application to this process.

The output from such a unit is not continuous but consists of "grouped series" of sparks separated by "dead" periods in which sparks are absent. It is shown both experimentally and also from a consideration of the nature of this output, that it is a matter of considerable importance to the success of the welding process, that these injected spark groups should be correctly phased relative to the main welding current, i.e., that correct phase adjustment should be made between the input supplies to the high frequency spark unit and the welding transformer.

The time durations of the phenomena here involved were of the order of a microsecond for individual sparks, a millisecond for the interval between individual sparks, 6 milliseconds for the spark groups, and 4 milliseconds for the "dead" period between successive spark groups. From a study of the oscillographic data together with the corresponding weld test runs, it was found that the optimum relative phasing for successful welding was such that the middle of the spark group occurred just after the welding current reached zero.

Correct phasing eliminated half cycle rectification when working to a work piece of an Al-5%Mg alloy, at an open circuit welding voltage of 60 V. r.m.s. Change of the relative phase position results in variation in the time delays to arc re-ignition in half cycles of reverse polarity (work piece negative). Such delays had a marked influence on current asymmetry, quite apart from the asymmetry which is normally present in the tungsten-aluminium arc unless special steps are taken for its prevention. In these investigations, the reverse polarity current decreased by some 30 per cent. per millisecond delay from the instant of current zero to arc re-ignition.

Effects are also noted consequent on changing the work plate material from an Al-5%Mg alloy to commercially pure aluminium, whilst the surface condition of the former was also found to influence results. The differences in behaviour were reflected in the oscillograms.

Some attention is also given to operational adjustments to the spark injector unit, bearing on its efficiency in promoting satisfactory welding; whilst a simple switching method is described for obtaining optimum phasing of the inputs to the h.f. spark injector unit and the welding transformer, for satisfactory welding.

1. INTRODUCTION

It is desirable for furthering the a.c. Argon arc method for welding aluminium that a detailed knowledge should exist of the electrical parameters involved in the process. This implies a knowledge of the characteristics both of the arc itself drawn between a tungsten electrode and an aluminium work piece in an atmosphere of argon, and of the power welding circuit together with any associated electrical equipment.

This welding process which has recently been discussed in relation to its application in industry,[1] presents a number of features of interest from the electrical standpoint, including mechanisms of re-ignition of the a.c. arc. At the end of every half cycle in such an arc, there is a brief period in which the current is almost zero, and during this period rapid de-ionization of the arc can occur, so that, as the voltage across the arc gap reverses, conductivity has to be re-established if the arc is to continue in the following half cycle. If the de-ionization has been severe, the voltage required to restart the arc may be considerably in excess of the arc burning voltage.

The general problem of arc maintenance, which intimately concerns a.c. Argon arc welding, is further complicated in this case by the unsymmetrical electrode arrangement of dissimilar metals, and because the open circuit voltage of the welding transformer has to be limited to about 100 V. r.m.s.

Inherent in this welding process therefore, is the tendency, unless means are adopted for its prevention, for the arc to fail to re-ignite on voltage reversal, this tendency being most apparent for the half cycles in which the aluminium work piece is about to become the effective cathode. This half cycle rectification, if at all marked, has a serious deleterious effect on the properties of the weld.

A method now in current practice for the prevention of this tendency to rectify is the injection across the arc, from a separate supply, of a series of h.f. oscillatory sparks. These sparks serve to break down the arc gap which might otherwise have become non-conducting.

It will be realised that the complete analysis of the electrical characteristics of this particular welding process involves the study of phenomena occurring in times of the order of a hundredth of a second, i.e., the ordinary 50 cycles per second phenomena, down to those taking place within microseconds, the order of time involved in arc re-ignition phenomena.

In the course of other investigations[2, 3] on welding arcs by the E.R.A. investigators, oscillographic recording equipments had been developed with time resolutions adequate for the recording of such phenomena, and it was decided to use these equipments to study this type of welding arc. Whilst the fundamentals of such an investigation concern arc re-ignition phenomena, details of actual re-ignition processes as such were not required at this stage, and the highest speed recording available was therefore not used.

Inquiry indicated that some uncertainty existed about the characteristics of the high frequency spark injector units commonly used in this Argon arc welding of aluminium, and their bearing on the process. The use of high frequency spark injection was mentioned some years ago by Piper[4] in connection with d.c. Heliarc welding, following which it was used with the a.c. Argon arc process when it was assumed to initiate the arc at the beginning of each half cycle. Although subsequent investigations have been pursued in relation to the electrical characteristics of this process, a full appreciation of the factors involved still appears incomplete. Oscillograms of arc voltage or current in published literature often are hand reproduced, ignoring the effects of the high frequency[5, 6], or else special test arrangements are adopted because of the difficulty of measuring and recording it.[7] Indeed, the temporal resolution of recording has been inadequate for the detailed examination of the high frequency spark phenomena associated with the process.

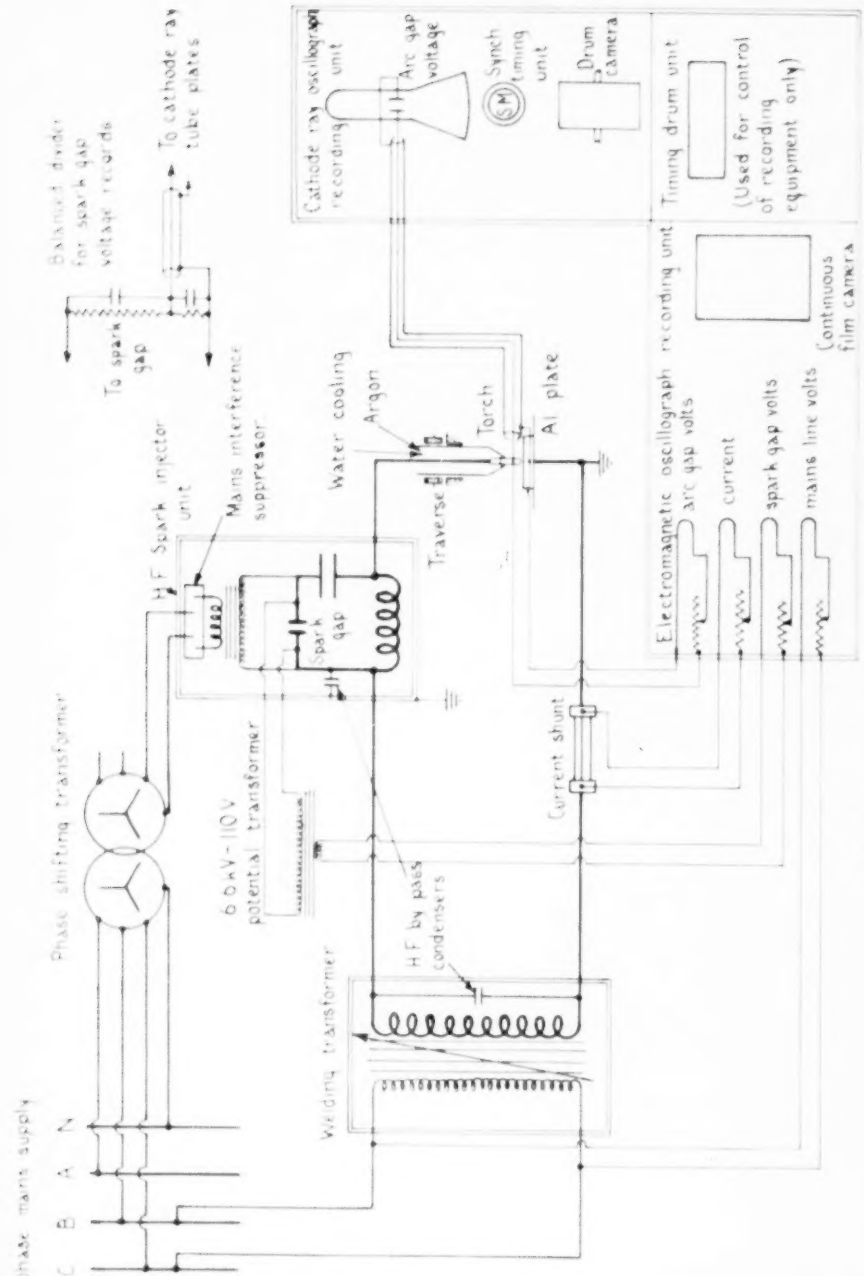


Fig. 1. Schematic diagram of test and recording equipment.

Further, in practice, similar results have not always been obtained on separate welding equipments, although both equipments and test conditions appeared to be the same. Most anomalies were encountered when using existing welding transformers in conjunction with separate high frequency spark injector units. Whilst the functioning does not always appear to be understood, such anomalies are usually absent on composite equipments supplied for the Argon arc welding of aluminium.

In this report the behaviour of a typical commercial high frequency spark injector unit has been examined in relation to this welding process. In further reports it is hoped to analyse other electrical features of the process, such as the effect of open circuit voltage, the effects arising from a large series capacitor in the main circuit, the short time electrical characteristics of the welding circuit, etc.

2. BRIEF EXPLANATORY DATA ON THE BEHAVIOUR OF THE H.F. SPARK INJECTOR UNIT

The commercial spark injector unit used in this work consisted of a high voltage transformer feeding into a series capacity inductance circuit in parallel with a spark gap. In every half cycle this type of unit produces a grouped series of sparks, the group occupying about two-thirds of the half cycle duration, with the duration of each spark being only of the order of a fraction of 1 per cent. of the time interval between sparks. Such an injector unit does not produce a continuous train of h.f. oscillatory sparks throughout the half cycle.

An analysis of the operation of this typical unit is given later in Section (6) of this report, and at this juncture it is sufficient to refer to Fig. 9 (c), which is a section of a cathode ray oscillogram taken across the spark gap of the unit. The record shows the build-up of voltage across the spark gap to its breakdown voltage, when the gap discharges. The process of voltage build-up and breakdown across the gap is then repeated, resulting in a series of individual spark discharges (see also sketches (*a*) and (*b*) in Fig. 10). A consequent impulse appears across the arc gap of the welding circuit for each individual spark discharge. The record makes clear the discontinuous nature of the output from such a unit, and illustrates the "grouped" form of the series of sparks in each half cycle, and the "dead" periods occurring between the groups.

It is the output from this unit that is injected into the welding circuit, so that the question of the phase relationship between the group of sparks, and the flow of current in the main welding circuit therefore arises. With the equipment here used, which may well be typical of actual practice, the welding transformer and the spark injector are separate units, and there is no automatic control of the phase relationship of their outputs, which largely depends on the connections which happen to be made to the three phase mains power supplies. Thus, unless definite adjustment is made, the spark group may be injected around the time when the current in the welding arc is passing through its zero, or when it is passing through its peak, or intermediately. It is clear that to be effective in assisting arc re-ignition, the spark group must be injected around and immediately following the time of current zero, when the arc, if it is to continue, has to restrike. For example, consider the case when, without superposed spark injection, the system is rectifying for the half cycles in which the work piece is cathode. If now the injector unit is switched in, but with its output so phased in relation to the current in the welding circuit that the spark group is injected around the time of current peak for the conducting half cycle, then the next group of sparks will not occur until well after the time of voltage reversal in the welding circuit. They will thus be ineffective in initiating arc gap breakdown early in the half cycle in which the work piece is cathode. Under such conditions it will be impossible for the injector unit to promote satisfactory welding.

From the above generalised statements it is seen that the phasing of the output of the injector unit in relation to the current in the main welding circuit must bear directly on the prevention of the partial or the complete half cycle rectification which can be encountered in the welding of aluminium, at open circuit voltages accepted as "safe" in practice.

To enable this phase relationship to be fully investigated in its effects on welding, a phase shifting transformer was incorporated in the supply to the spark injector unit, enabling any phase adjustment to be made between the spark group and the main welding current. The method of test procedure and the experimental results from this work are considered below.

3. ELECTRICAL PARAMETERS AND THEIR OSCILLOGRAPHIC RECORDING

A description of the recording equipment used, comprising both electromagnetic and cathode ray oscillographic units has already been published elsewhere,[2] so that details are not given here. In the present investigations the equipment was operated so as to give a time scale of 10 millisec. per cm. on the electromagnetic oscillograms, and 3 millisec. per cm. on the cathode ray records.

The parameters recorded either on the electromagnetic or cathode ray oscillographic units, or on both, as required, were (*a*) supply mains voltage, (*b*) current in the main welding circuit, (*c*) voltage across the arc gap together with the superposed voltage from the h.f. spark injector unit and (*d*) the voltage across the spark gap of the injector unit.

The duration of the recording time was one second, the equipment being triggered in 45 seconds after arc initiation in the welding circuit. (See Section 4.2.)

4. TEST ARRANGEMENTS

4.1 Test Circuit Settings and Equipment

A schematic diagram of the test circuit is given in Fig. 1, power being derived from a leaky reactance type welding transformer at 50 c/s. Whilst it is known that this type of transformer is not the most suitable for this particular welding process, it was adequate for the work in hand.

The current setting for these tests was nominally 60 r.m.s. amperes at a nominal open circuit voltage of 60 V. r.m.s., whilst argon gas (purity 99·8 per cent.) flow was adjusted to read 4 litres per min. The open circuit voltage was low compared with usual practice, but was more suitable for examining the particular phenomena with which this report is concerned. To investigate the efficacy of the spark injection for arc maintenance, it was necessary that the arc should show a definite tendency to rectify, which is more apparent at lower open circuit voltages.

As already stated in Section (2) above, the h.f. spark injector unit was of an ordinary commercial type, but with a phase shifting transformer incorporated in the input circuit. A hand, water-cooled, Argon arc welding torch was used, fitted with a 3.32 in. diameter tungsten electrode. The torch was clamped to an electrically driven traverse machine moving at 1 mm. per sec., and the electrode gap was fixed at $\frac{1}{8}$ in.

The main series of tests reported upon here were made on 12 in. by 4 in. by $\frac{1}{4}$ in. work plates of an Al-5%Mg alloy. Plates of commercially pure aluminium (2L4), but $\frac{1}{4}$ in. thick, were also used.

4.2 Test Procedure

With the power circuit energised, the traverse machine and the spark oscillator were switched on together, the latter initiating the arc. At the end of each of the test runs, which were 6 cm. long, the spark oscillator was switched off, resulting in arc extinction.

The work plates used in the main series of tests were clamped to, but spaced from, a brass table, cooling effects thus being limited and reproducible. Current was fed symmetrically into the work piece from below.

The runs were made without a filler rod, and in conjunction with the oscillographic evidence, their appearance indicated the suitability of the test set up from the welding standpoint. The recording gear was triggered in 45 sec. after arc initiation, by which time the system was assumed to have reached a state of quasi equilibrium, so that the oscillographic recording period of one sec. could be taken as providing data typical of the run.

The phase relationship between the spark group from the injector unit, and the current in the welding circuit was altered from test to test by means of the phase shifting transformer, all other test settings remaining unchanged.

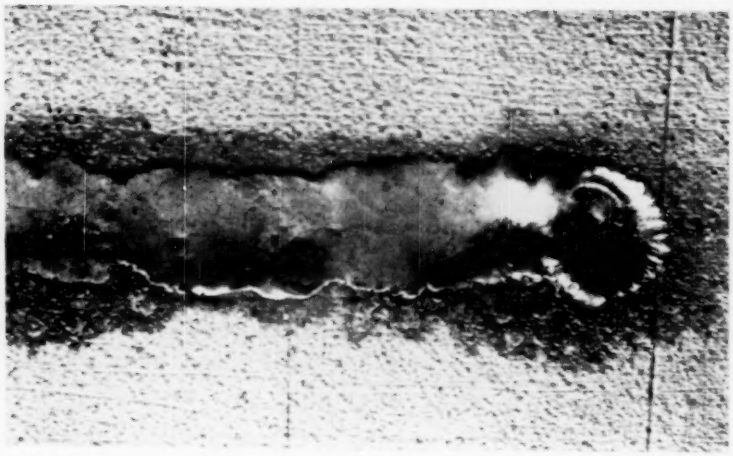


Fig. 2(a) 0° (180°). *Right*

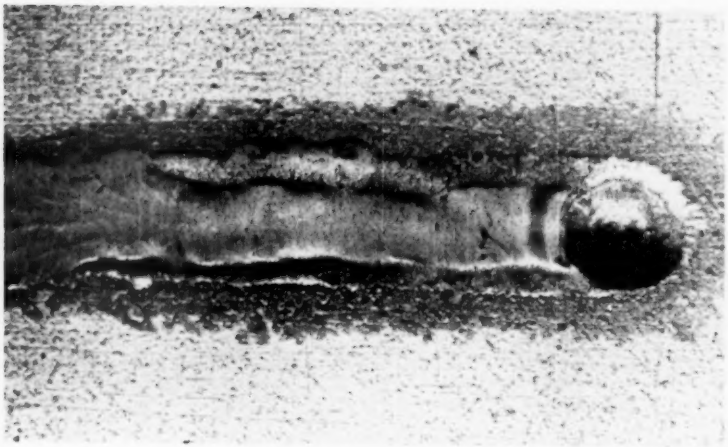


Fig. 2(b) 30° (210°). *Left*

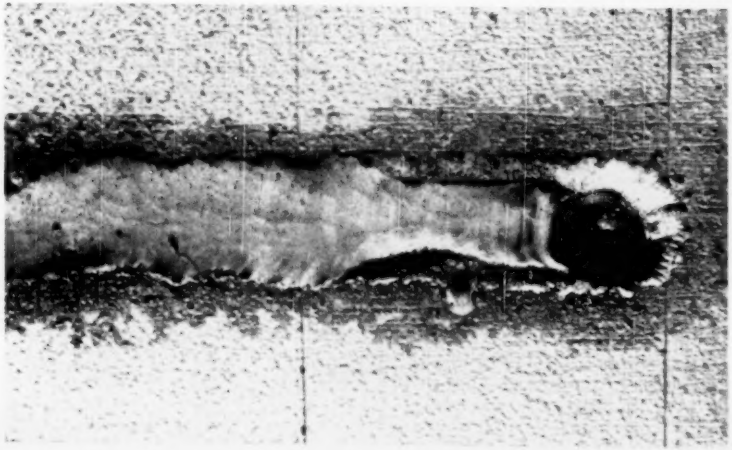


Fig. 2(c) 60° (240°). *Right*

Melt runs on Al-5%Mg Aluminium alloy (surface scratch brushed) against degrees lead of H.F. injector unit input, relative to welding transformer input. (Phases 180° apart, result in similar runs.)

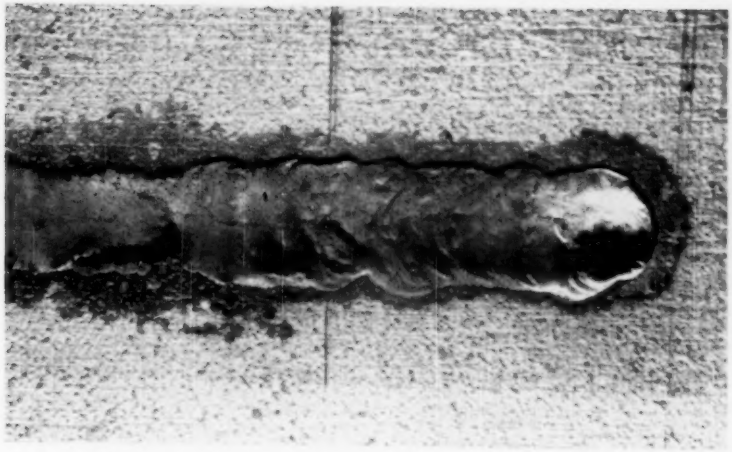


Fig. 2(d). 90° (270°).

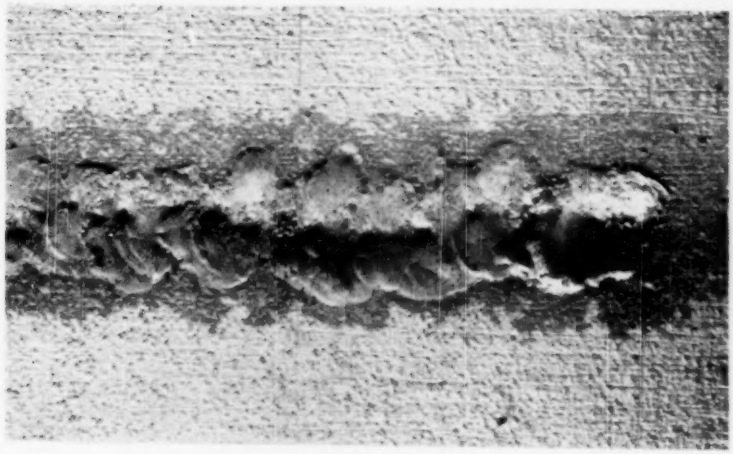


Fig. 2(e). 120° (300°).

Melt runs on Al-5%Mg aluminium alloy (surface scratch brushed) against degrees lead of H.F. injector unit input, relative to welding transformer input. (Phases 180° apart, result in similar runs.)

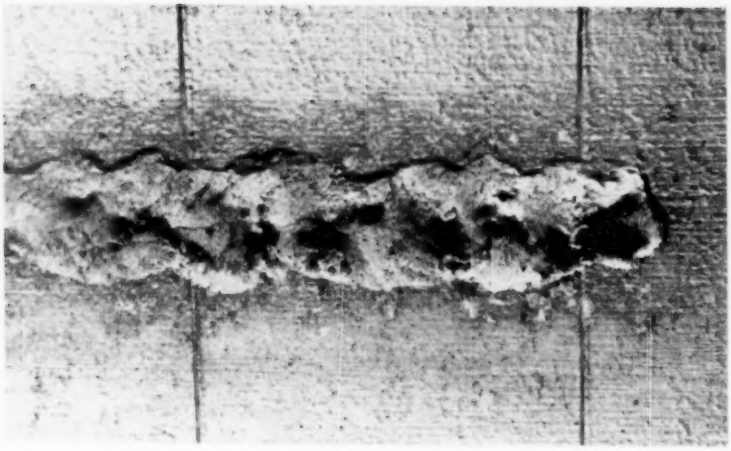


Fig. 2(f). 135° (315°). ×5.

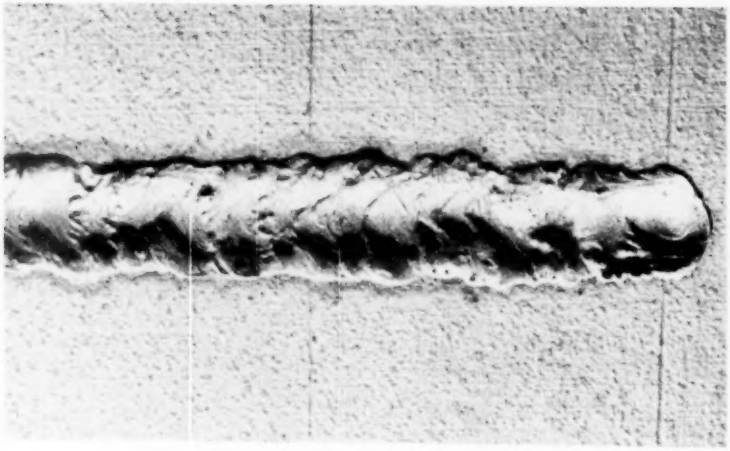


Fig. 2 (g). 150° (330°). ×5.

Melt runs on Al-5%Mg aluminium alloy (surface scratch brushed) against degrees lead of H.F. injector unit input, relative to welding transformer input. (Phases 180° apart, result in similar runs.)

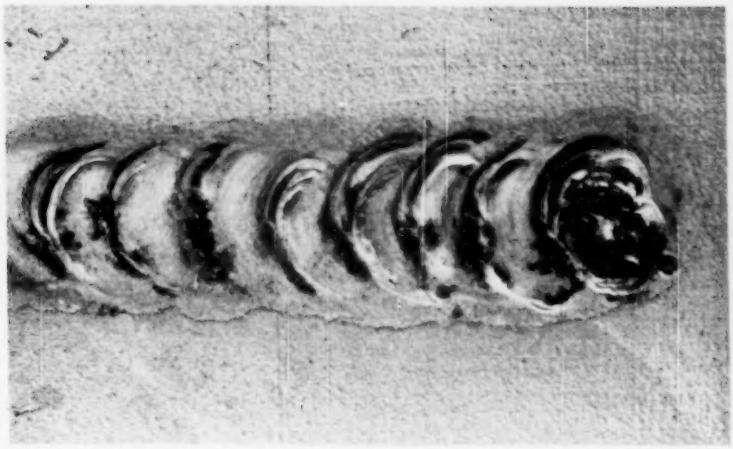


Fig. 3(a). 60°.
Right.

×5.

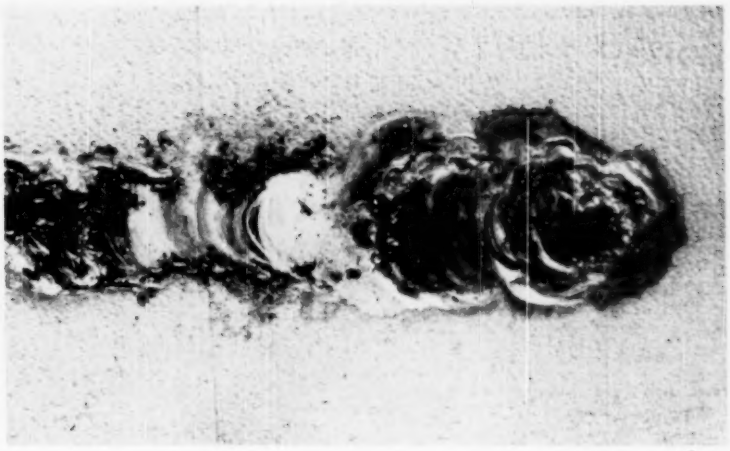


Fig. 3(b). 120°.
Left.

×5.

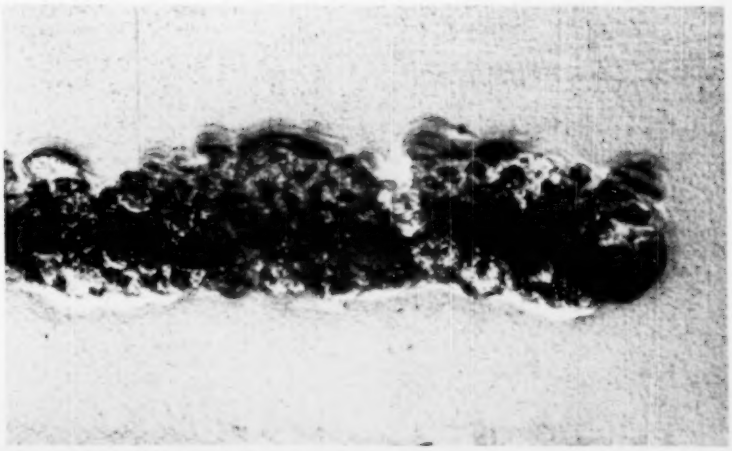


Fig. 3(c). 150°.
Right.

Melt runs on commercially pure aluminium (surface scratch brushed), against degrees lead of H.F. injector unit input relative to welding transformer input.

×5.

5. EXPERIMENTAL DATA ON EFFECTS OF SPARK GROUP PHASING

5.1 General Observations

With experimental conditions as above a series of runs was made on an Al-5% Mg alloy with phase shifts normally set in 30 deg. steps from 0 deg. to 360 deg. Oscillographic recordings, to be discussed in the next section, were taken for each run, whilst general observations were made of the behaviour of the arc, etc.

It was evident that changing the phase of the spark group relative to the power circuit could vitally affect the welding process and that a phase reversal (180 deg. shift) produced no marked change. At phase displacements of 0, 30, 60, and 90 deg. (and correspondingly 180 deg. to 270 deg.) the arc quickly started after energising the h.f. injector unit, and progressed steadily along the degreased but otherwise untreated surface work plate, with the formation of a continuously moving weld pool. Similar results obtained for a surface scratch brushed before use, except that there was a tendency for the arc to splutter slightly, whilst a delay of a second or so was apparent before arc ignition following switching on the h.f. spark unit.

For phase displacements of 120 deg. and 135 deg. (300 deg. and 315 deg.) the arc was again quickly started on the untreated surface work plate, but spluttering was now evident throughout the run, accompanied by rapid fluctuations in light output. The arc under these circumstances appeared to progress along the plate in a series of small jumps from spot to spot. Further, the sound output from the welding transformer under these conditions of operation was subject to erratic variation as against a steady hum. Similar results were noted for a scratch brushed surface, but with the arc starting time delay increased to something of the order of 5 seconds.

At 150 deg. (and 330 deg.) phase displacement the arc started quickly on the degreased work plate, and although steady, it progressed along the plate in a series of small jumps. Slight arc splutter with variation of light output was evident on the scratch brushed surface, with again the somewhat increased time to arc initiation at the beginning of the run.

The appearance of the resultant runs for a scratch brushed alloy surface can be seen in Fig. 2. For the first four phase displacement positions (0 deg. to 90 deg. group) the run is seen to be continuous, with the 30 deg. and 60 deg. positions exhibiting slightly more favourable characteristics than the 0 deg. and 90 deg. positions. The appearance of the run, however, becomes roughened and irregular at 120 deg. (and 135 deg.), whilst for the last setting at 150 deg. it is strongly "pitted."

The effects of phase displacement between the inputs to the spark injector unit and the welding transformer are also visually apparent in the case of runs on a commercially pure aluminium work plate. Fig. 3 is a photograph of runs on such a plate for phase settings of 60 deg., 120 deg. and 150 deg.; the deterioration in appearance being clearly evident, and considerable blackening of the run is apparent in the last position.

The descriptive matter in this section should be considered in relation to the curves in Fig. 5 which have been derived from the oscillographic data dealt with in Section 5.2.

5.2 Oscillographic Data for Al-5% Mg Alloy

5.2.1 Surface only Degreased before use

An analysis of the cathode ray oscillograms for a series of tests made with the above alloy as work piece illustrates very clearly the importance of correct spark phasing.

The half cycles of interest are those in which the work piece was about to become the cathode, and when attempted rectification is encountered.

In this present analysis, distinct classes of breakdown from open circuit voltage to arcing conditions have been recognised. Firstly, breakdown may occur almost immediately after current zero on voltage reversal, this constituting the most favourable condition from the welding standpoint. A section of an oscillogram exhibiting this class of breakdown is shown in Fig. 4 (*c*). Secondly, appreciable delay up to some considerable fraction of a half cycle duration may occur before breakdown. This is a far less favourable condition than early breakdown, the delayed breakdown being illustrated in the section of the oscillogram shown in Fig. 4 (*g*). Lastly, breakdown may fail completely, giving the condition of full half cycle rectification as shown for example in one half cycle in Fig. 4 (*e*), (or Fig. 6 (*c*) for commercially pure aluminium).

The record for each setting of the phase shifting transformer, i.e., for each phase position of the spark group relative to welding current, was analysed for the class of breakdown. The numbers of the half cycles in which breakdown occurred "early" and "late" were determined, together with the number of half cycles, if any, in which rectification occurred, and were plotted against the phase setting. (Illustrative sections of oscillograms are reproduced in Fig. 4 (*a*) to (*g*) for a series of relative phase positions.) The results of the analysis are shown in Fig. 5 (*a*), in the derivation of which, breakdown has been termed "early" if taking place within 1·5 milliseconds of the voltage reversal, and "late" if in excess of this time. The selection of the time period of 1·5 milliseconds, although somewhat arbitrary, does derive from experimental findings, and from a general consideration of the extensive oscillographic data available. With breakdown occurring fairly regularly within 1·5 milliseconds, the appearance of test runs was satisfactory, whilst current asymmetry, introduced as a result of this delay time to arc re-ignition, was not too serious (see Section (5.4).) It is also the approximate time, in the circuit used, for the voltage, after reversal at the end of the previous half cycle, to reach its peak open circuit value, assuming breakdown to arcing conditions had not occurred before the attainment of this peak. With this division, no difficulty was entailed in the analysis, since in general, breakdown occurred either well within or well outside this time limit.

In Fig. 5 the relative phase displacements of spark group and welding current from 180 deg. to 360 deg. have been combined with the corresponding positions on the 0 deg. to 180 deg. scale, as the results were substantially the same. Three curves are shown: curves A and B referring respectively to early and late half cycle breakdown, whilst curve C gives the percentage number of half cycles which completely rectified. The percentage of each class of breakdown at each phase position is based on the analysis of at least 100 cycles.

Fig. 5 (*a*) shows that from about 0 deg. up to about 90 deg. phase displacement, the number of half cycles breaking down early is 100 per cent. After 90 deg. conditions begin to deteriorate, with the percentage of early breakdowns decreasing rapidly, and the percentage of late breakdowns and rectifications increasing, with a minimum of early breakdowns occurring at 150 deg. After this setting conditions again improve, the curve of early breakdowns rising fairly steeply so that by about 180 deg. the 100 per cent. early breakdown condition is again achieved.

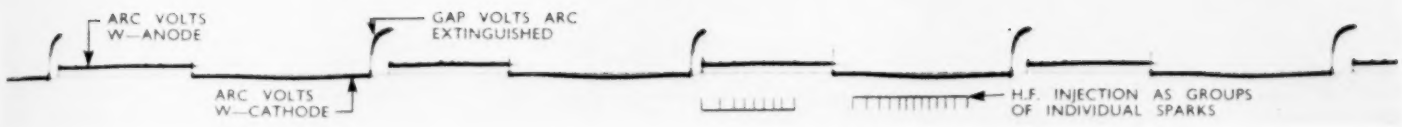
It should be borne in mind that spark injection was not absent in those half cycles which failed to break down, Fig. 5 (*a*), curve C. The "rectifications" in most cases correspond to spark group injection so late in the half cycle that the open circuit voltage has decreased to such an extent that the arc does not strike in spite of spark injection. (See rectified half cycle in Fig. 4 (*e*).)

The characteristics of the curves in Fig. 5 (*a*) show very clearly the important bearing on this welding process of the phase relationship between the spark group and the welding current. Further consideration will be given to the shape of the several curves in a subsequent section of this report.

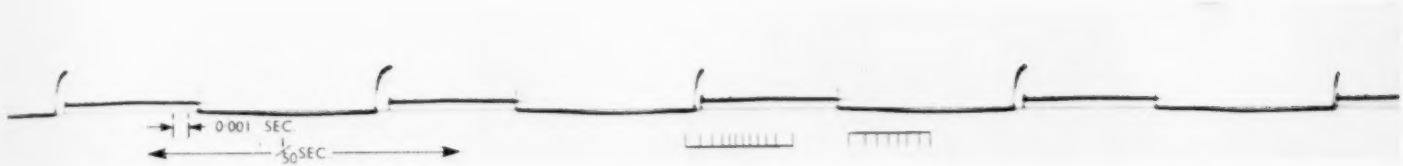
5.2.2 Surface Scratch Brushed before use

The same procedure as for the degreased alloy surface was followed for tests on the same alloy, scratch brushed immediately prior to use. It was clear from the oscillograms that under otherwise identical test conditions, there were differences resulting from surface state, although general characteristics in relation to spark group phasing were the same.

Curves corresponding to those given in Fig. 5 (*a*), but for the scratch brushed alloy are shown in Fig. 5 (*b*). It will be seen that whilst the general conclusions as to spark group phasing are the same, the shape of the three curves in the latter figure have undergone some modification from the corresponding curves in Fig. 5 (*a*).



(a) 0° lead. (Injector unit input relative to welding transformer input).

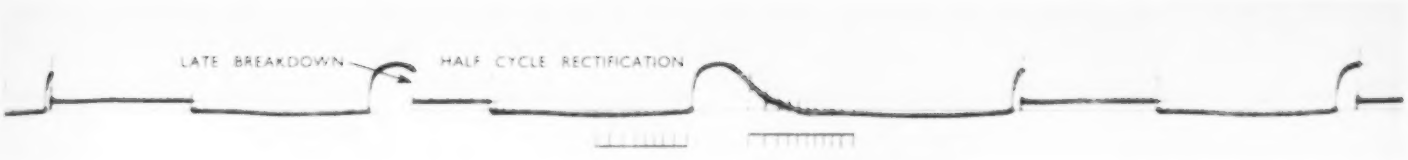


(b) 30° lead.

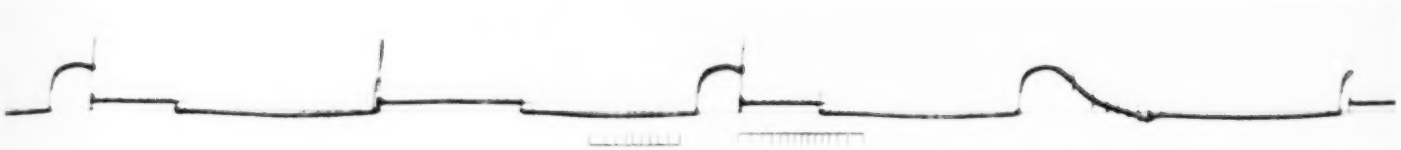
(c) 60° lead. See also Fig. 7(a).

(d) 90° lead.

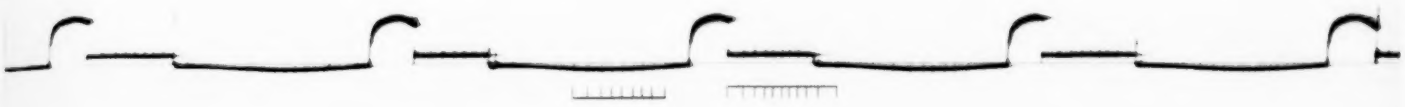
Fig. 4. Cathode ray oscillograms of arc gap voltage (together with H.F. injection) for Al-5%Mg alloy (surface degreased), showing effects of phasing of H.F. input relative to input of welding transformer. Timing Marks—1 millisec. dashes, time from left to right 15 millisec./cm. Voltage deflection upwards for tungsten electrode positive. Voltage zero on timing line, calibration 115 V/cm.



(e) 120° lead. See also Fig. 7(b).



(f) 135° lead.



(g) 150° lead. See also Fig. 7(c).

Fig. 4—*continued.*

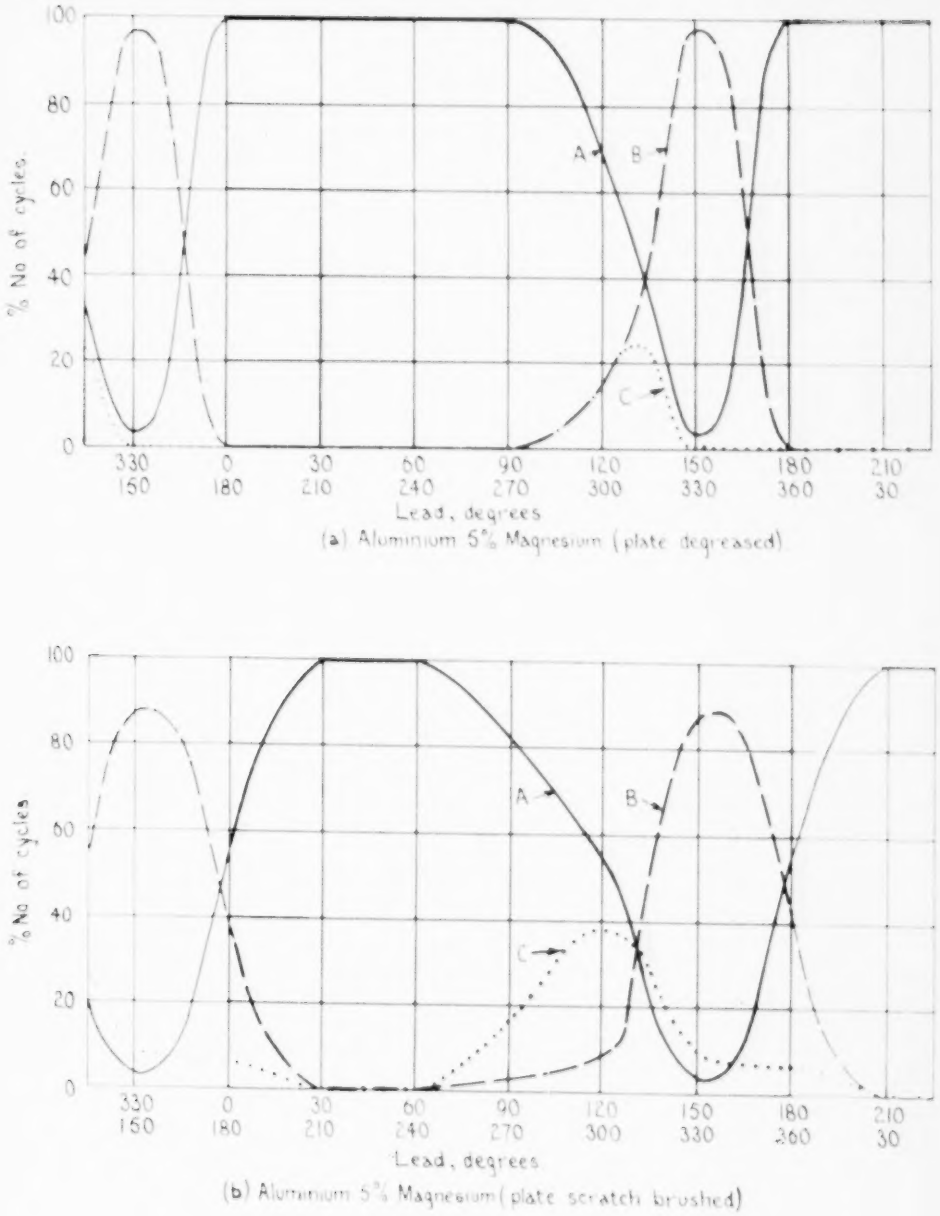


Fig. 5. Effect of phasing on arc initiation (Al. plate negative).

A. Arc re-ignition within 1·5 millisec. of current zero.

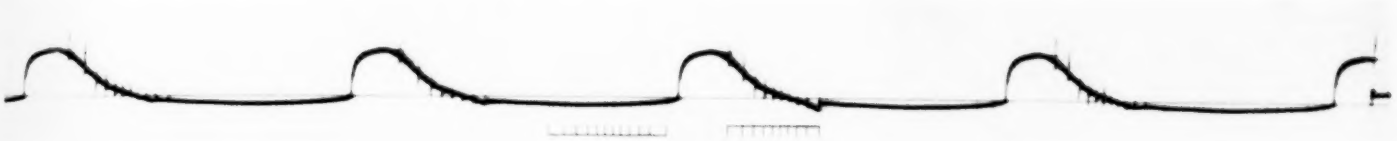
B. Arc re-ignition after 1·5 millisec. of current zero.

C. Complete rectification (plate negative).

"Lead" in both figures refers to H.F. injector unit input relative to welding transformer input.

(a) 90° lead for Al-5%Mg alloy (surface scratch brushed). *Cf.* Fig. 4(d).

(b) 60° lead for commercially pure aluminium (surface scratch brushed). *Cf.* Figs. 4(c) and 3(a).



(c) 150° lead for commercially pure aluminium (surface scratch brushed). *Cf.* Figs. 4(g) and 3(c).

Fig. 6. Cathode ray oscillograms of arc gap voltage (together with H.F. injection), showing effects arising from first spark after voltage reversal failing to start arc. (Calibrations, etc., as for Fig. 4.)

The settings for maximum early breakdowns are more limited with the scratch brushed surface work plate than with the degreased plate, a falling off from optimum conditions appearing after 60 deg. phase displacement. The actual minimum of early breakdowns as before occurs at 150 deg., but the following rise to optimum conditions is more gradual. It is thus seen that the phase setting of the spark group is more critical with the scratch brushed work plate than with the degreased only surface. This difference is a matter of interest. A comparison of the oscillographic data for the degreased and scratch brushed surface work plates, reveals that whilst in the former case, in general, the first spark injected after voltage zero was effective in causing breakdown to arcing, in the latter case, quite often, several sparks were injected before arc re-ignition occurred. This necessity for multiple sparks occasioned delay in half cycle breakdown, with the tendency therefore for the number of "late" breakdowns, or rectifications, to increase, resulting in the optimum position for spark injection becoming more critical. See Fig. 6 (*a*) and compare with Fig. 4 (*d*).

It must be remembered that the details of this analysis are applicable only to the particular test conditions here used. It is clear, for example, that the shape of the curves A in Fig. 5 might be altered by alteration in open circuit welding voltage, and that an increase in the voltage of the spark injection might mask the work plate surface effect discussed above, although, of course, a definite statement on this matter would require more knowledge of the fundamentals of this surface effect. The general conclusions as to spark group phasing, however, apply to any spark injector unit of a type similar to that used in these investigations.

5.3 Tests on Commercially Pure Aluminium

In addition to the work on the Al-5%Mg alloy, a limited number of tests were made using work pieces of commercially pure aluminium (2L4). No alterations were made in test conditions from those previously obtaining. Data from this work fully supported the conclusions drawn from the investigations on the Al-5%Mg alloy as to the importance of spark group phasing. Reference has already been made to Fig. 3, showing the difference in appearance between runs on a commercially pure aluminium work piece for three main spark group phase positions, viz., 60 deg., 120 deg. and 150 deg.

Effects additional to those pertaining to the question of phasing were, however, evident. For example, under the test conditions obtaining, a group of suitably phased sparks would sometimes fail completely to cause breakdown to arcing (see Fig. 6 (*b*)). In general, arc initiation does not appear to be so readily achieved with the pure aluminium as with the alloy, e.g., compare Figs. 6 (*b*) and 4 (*c*), also Figs. 6 (*c*) and 4 (*g*). This implies that change in work piece material, and/or its surface condition, have introduced additional factors which complicate or preclude an independent study being made of spark group phasing effects under the same particular test conditions as used for the Al-5%Mg alloy. A limited increase in welding voltage, or of spark gap voltage, or in rate of argon gas flow, might facilitate arc re-ignition, under which circumstances, with the first spark or early subsequent spark causing breakdown, comparable spark group phasing effects to those derived for the Al-5%Mg alloy are to be expected.

5.4 Effect of Current Zero Pause on Current Magnitude

In the present investigations no attempt was made to eliminate or control the d.c. component of the welding current, and no series condenser was inserted in the welding circuit, so that half cycle current asymmetry was encountered.

In general, when the tungsten rod is hot, the arc re-ignites more readily when the tungsten, rather than the aluminium, becomes negative. For the test conditions here used, the current always restarted immediately on voltage reversal, when the tungsten became the effective cathode if the previous half cycle (aluminium cathode) had conducted for an appreciable time. If the arc had extinguished or rectified in this previous half cycle, then the h.f. spark injection re-ignited the arc soon after the o.c. volts had changed polarity (tungsten negative). When the aluminium became negative, however, the arc always extinguished after the previous half cycle, and did not restrike without the h.f. injection. Thus, there is only appreciable current zero pause for the half cycle in which the aluminium is negative, and this pause is obviously affected by the phasing of the spark group, giving "early" breakdowns or otherwise.

The increasing degree of current asymmetry resulting from increase in delay to re-ignition of the arc or complete rectification is illustrated by the electromagnetic oscillograms of arc current and gap voltage shown in Fig. 7. These oscillograms are for phase shifts of the input to the spark injector unit with respect to the welding circuit input of 60 deg., 120 deg. and 150 deg., the corresponding cathode ray oscillograms being given in Fig. 4 (*c*), (*e*) and (*g*) respectively.

It can be seen that the current loop, for the tungsten as cathode, is approximately constant in magnitude, whilst that for the aluminium as cathode varies down to zero (i.e., rectification), and at its best does not equal that for the tungsten.

From such current records (from the electromagnetic oscillograms), and the time delay to arc re-ignition (derived for greater accuracy from the corresponding cathode ray oscillograms of arc voltage), curves of current peak and current area against duration of current zero pause were derived as in Fig. 8 (*a*) and (*b*) respectively. These curves are plotted as a percentage of the maximum current peak or current area (for the aluminium as cathode) for effectively no zero pause. The variation of current for the tungsten as cathode was small, and therefore only the average (with an indication of the deviation) current peak and current loop area have been plotted on Fig. 8 (*a*) and (*b*) for these half cycles.

The curve in Fig. 8 (*a*) shows that the peak of the current in the reverse polarity half cycle decreases by about 25 per cent. per millisecond delay to arc re-ignition, whilst the quantity of current flowing decreases by about 30 per cent. per millisecond delay (Fig. 8 (*b*)).

The d.c. component can be derived from the difference between the current loop areas for the aluminium and tungsten half cycles given in Fig. 8 (*b*). It can be seen that the d.c. component increases with increasing delay to re-ignition of the arc (aluminium negative) and therefore also depends on the relative phase of the inputs of the spark oscillator and the welding transformer.

It is outside the scope of this present report to discuss what effect this current asymmetry has on the properties of the weld, the degree of saturation of the welding transformer, or the primary current wave form and effective power factor.

6. THE H.F. SPARK INJECTOR UNIT

6.1 General Operational Characteristics

The performance and operational characteristics of the typical commercial spark injector unit here used present a number of points of interest. As these characteristics bear directly on the application of the unit to the welding process, and are common to all injector units working on the same principle, they have been considered here in greater detail. From such an analysis of the performance of the spark gap oscillator, the shape of the curves in Fig. 5 can be predicted.

Though there is nothing novel about the commercial unit used in this work, there appear to be certain misconceptions about the general behaviour of such a spark gap oscillator, as a source of high voltage high frequency for injection into the welding circuit. In essence, a condenser with a spark gap in parallel is charged from a relatively high impedance source to the voltage at which the spark gap of the unit breaks down, and the condenser is then very rapidly discharged through the gap. This cycle of operations is then repeated, the frequency of repetition being governed by the time constant of the condenser and the charging impedance, and the available H.T. voltage in relation to the breakdown voltage of the spark gap. This repeated cycle of operations has already been referred to in Section (2), and an oscillogram typical of the process for an alternating high voltage supply is shown in Fig. 9 (*c*). The condenser discharge is oscillatory, a small inductance

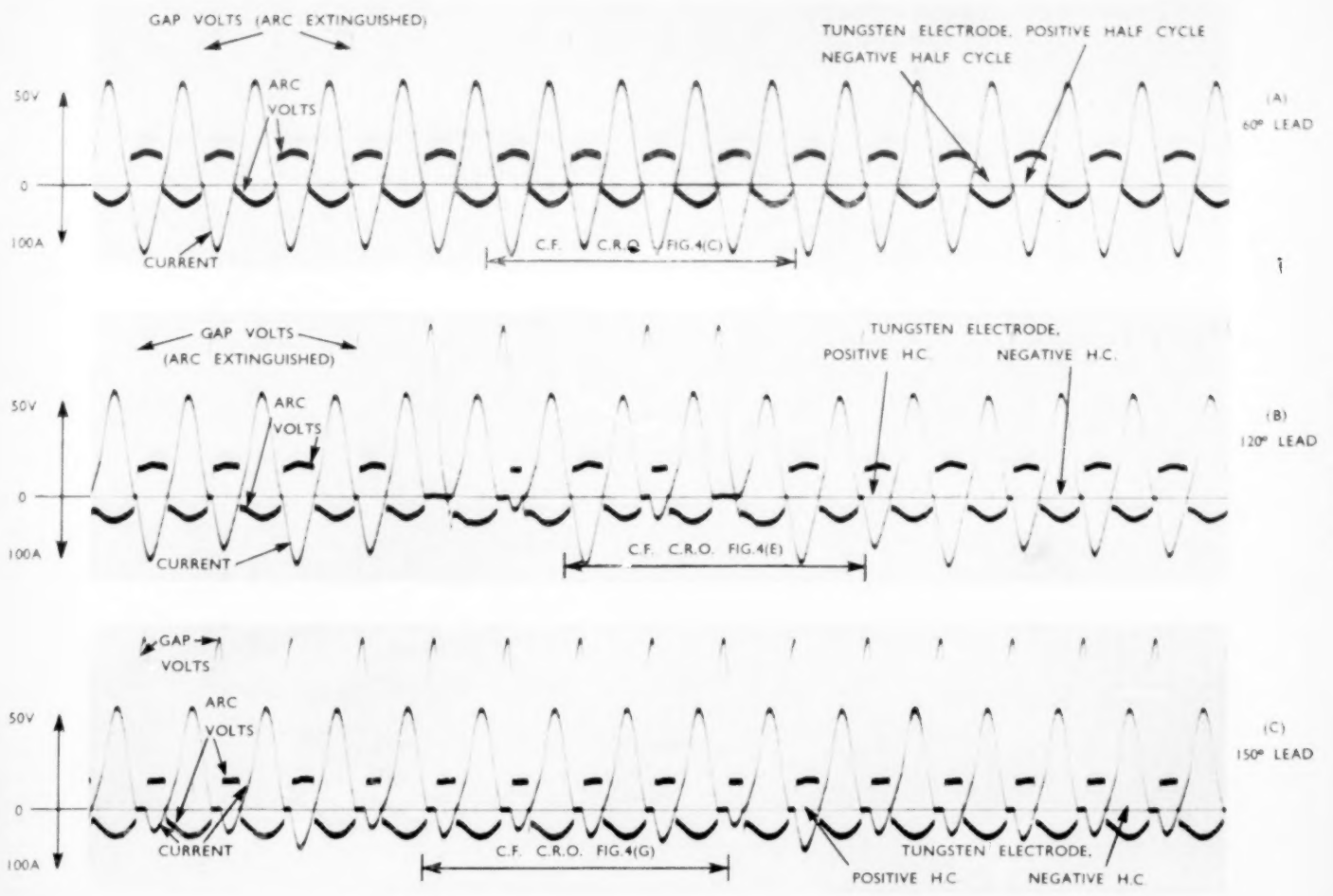


Fig. 7. Electromagnetic oscillograms of arc gap voltage and current against phase of H.F. injector unit input. (Reproductions 3/5 original, time left to right, calibrations voltage 29 V/cm., current 93 A/cm.)

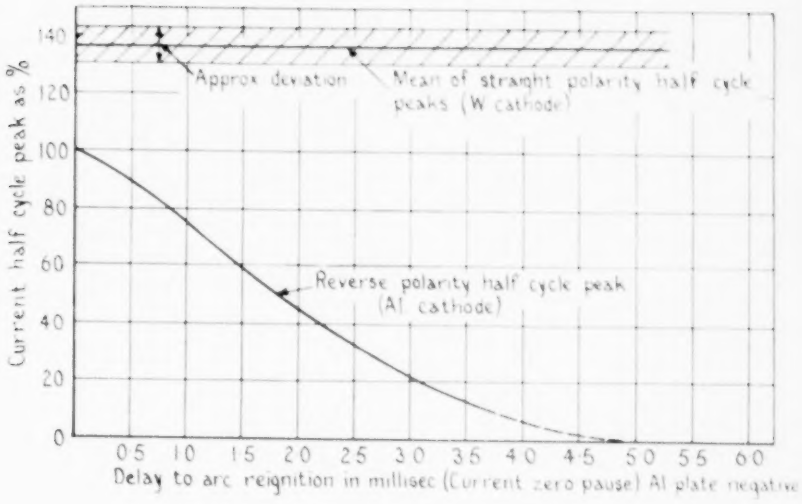

Current half cycle peak as %
140
120
100
80
60
40
20
0
Approx deviation
Mean of straight polarity half cycle peaks (W cathode)
Reverse polarity half cycle peak (Al cathode)
05 10 15 20 25 30 35 40 45 50 55 60
Delay to arc reignition in millisec (Current zero pause) Al plate negative

Fig. 8(a). Peak of current half cycles—current zero pause.

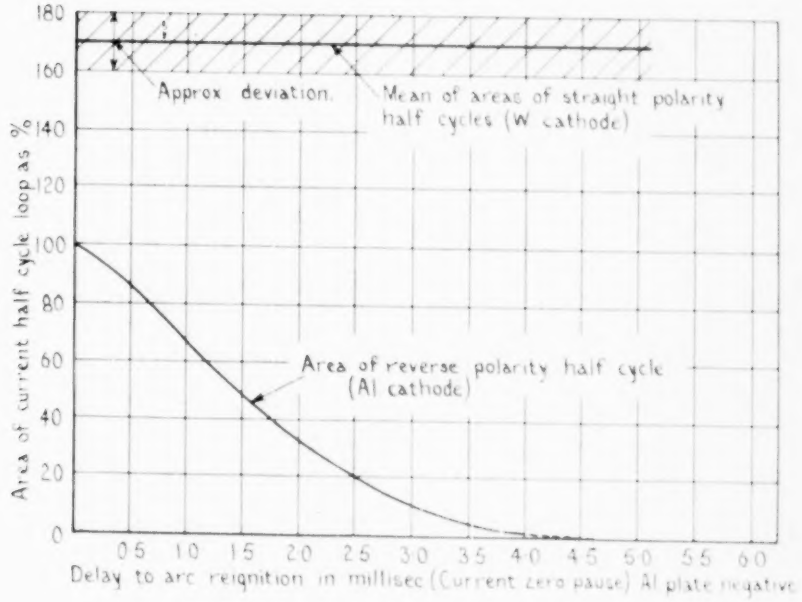


Fig. 8(b). Area of current half cycles—current zero pause.

(a) Single spark gap 1/32 in. width.

(b) Single spark gap 1/16 in. width.

(c) Single spark gap 1/32 in. width—half normal input voltage to unit.

(d) Triple spark gap 1/16 in. total width—all gaps "normal."

(e) Triple spark gap 1/16 in. total width—one gap "misfiring."

(f) Triple spark gap 1/16 in. total width—two gaps "misfiring."

Fig. 9. Cathode ray oscillograms of voltage across spark gap of H.E. injector unit. (See table.) Calibrations, voltage 3.3 kV/cm. approx. (positive upwards). Time (*left to right*), 5 millisec./cm. approx.

between the condenser and the spark gap resulting in a damped high frequency oscillation, a series of such damped oscillations being injected into the welding circuit.

In such a spark unit as here used, the oscillations are rapidly damped out in a time which is small compared with the charging time of the condenser. This charging time itself is, however, small compared with the duration of a half cycle, nominally 10 milliseconds, so that the device operating on high voltage a.c. results in a group of individual sparks (condenser oscillatory discharges) in each half cycle. The time interval between groups of sparks, the "dead" period referred to in Section (2), is the time taken (from the last spark in a group) for the a.c. to reverse polarity and for the voltage to again reach the breakdown voltage of the spark gap. In the present instance the duration of the high frequency damped oscillation (the spark) was of the order of a microsecond, whilst the interval between sparks in the group was normally of the order of a millisecond, but down to about a tenth of this time under particular and abnormal operating conditions. The "dead" period duration was usually about three to four milliseconds, but under abnormal conditions this could increase to some 8 milliseconds.

It is seen that the injector unit and all such of a like type are not sources of "continuous" high frequency.

6.2 Effect of Spark Gap Settings on Performance

It is clear from the foregoing section that the number of sparks injected in a given group of sparks, is governed not only by circuit components of the oscillator unit, but also by the nature and setting of the spark gap itself.

In the present investigations both the number of gaps, and the gap setting were varied, and the oscillograms, taken for each of the several conditions, showed interesting effects bearing directly on the efficacy of the injector unit in relation to welding. The series of tests on the spark gap were as follows:—

(i) Single gap, total gap 1/32 in., full input voltage to unit (240 V.).
(ii) As (i) but gap length increased to 1/16 in.
(iii) As (ii) but gap length increased to 1/10 in.
(iv) As (iii) but gap length decreased to 1/12 in.
(v) As (i) but input voltage to unit reduced to half (120 V.).
(vi) Triple gap, total gap 1/16 in., input volts to unit 240 V.
(vii) As (vi) but with one of the three gaps "misfiring."
(viii) As (vi) but with two of the three gaps "misfiring."

Sections of cathode ray oscillograms are reproduced in Fig. 9 (*a*) to (*f*) showing the voltage across the spark gap of the injector unit for a number of the above cases and it is clear that differences in operation can be very marked. A comparison of the spark gap behaviour is shown in the Table (p. 65*s*) in terms of the breakdown voltage and average number of sparks in a half cycle, etc. The approximate potential at which the spark gap broke down in the majority of cases in any one test is the main breakdown voltage given, while the additional voltages are a measure of the instability of the gap. The average of the number of sparks occurring in a group are derived in each case from some 50 cycles, and the standard deviations are included to indicate the spread in the number of sparks per half cycle group. These average figures are not given in the case of a single gap, 1/32 in. in width and with full input voltage, as this condition resulted in erratic but interesting operation of the gap (see oscillogram in Fig. 9 (*a*)). The voltage at which the gap broke down was subject to considerable fluctuation, whilst periods occurred during which the gap remained continuously conducting, with consequent cessation of the sparks, which periods in many instances added considerably to the "dead" period between spark groups. (See Section (6.1).) Such operation is obviously unsatisfactory for application in the welding process.

In an attempt to improve this operation therefore the gap was increased, first to 1/16 in. and then to 1/10 in. under otherwise similar conditions. Fig. 9 (*b*) illustrates the result for the 1/16 in. gap, which is seen to be less unsatisfactory than for the 1/32 in. gap, although still irregular as indicated by the standard deviation in the table, whilst the conducting periods occurred in some 25 per cent. of the total number of half cycles recorded, as against about 50 per cent. for the 1/32 in. gap.

With a gap of 1/10 in. breakdown only occurred once per negative half cycle and failed entirely with slight variation of circuit conditions. Although single sparks, injected for alternate half cycles (work piece the new cathode), might seem a favourable condition of operation for welding, the above arrangement only attained this condition at the expense of stability, and it was not suitable for practical use. The gap setting was therefore decreased again slightly, from 1/10 in. to 1/12 in. Whilst the resultant record showed much less irregularity than for the 1/16 in. gap, it still revealed similar characteristics.

Thus, for the full applied input voltage, the adjustment of the single spark gap for satisfactory operation was not easy on the unit used, unless special facilities were incorporated. The gap setting was therefore re-set to 1/32 in. and the input voltage to the injector unit halved to 120 V. r.m.s. The oscillogram in Fig. 9 (*c*) and the data in the table show that under these conditions the regularity of operation was satisfactory.

Without further investigation, however, the authors were not prepared to say what effect, if any, the lowered input voltage to the injector unit would have on its use with the particular welding process under consideration. Input voltage was therefore restored to full value whilst the spark gap of the unit was altered from single to triple, with a total gap of 1/16 in. The corresponding figures in the table for this arrangement, and the oscillogram in Fig. 9 (*d*), show operation under these conditions to be regular and satisfactory, whilst in practice it proved to be reliable over long periods of time. This triple spark gap was used as standard in the present investigations. A further point in favour of the triple gap, as against the single, was that it gave warning of when it needed cleaning, whilst the unit still functioned as a source of injection into the welding circuit. This arose because it is possible for either one or two of the three gaps to "misfire" whilst the remaining gaps or gap spark down, oscillograms of the resultant output under these conditions being shown in Fig. 9 (*e*) and (*f*). "Misfiring" of a gap in this case was evidenced by the discharge originating from a fixed part of the electrode and not at random all around it, this presumably implying a point of preferred breakdown or emission and consequently a much-reduced breakdown voltage for that particular gap of the three. It will be seen from data in the table, and from the corresponding oscillograms, that the average number of sparks per half cycle group increases as first one gap, and then two gaps "misfire," whilst the overall breakdown voltage decreases. This increase in numbers is not necessarily an advantage, since once the arc has re-ignited the remainder of the series is unnecessary.

Bound up with the question of the number of sparks per half cycle, the mode of operation and breakdown voltage of the spark gap, etc., is the problem of radio interference from equipment of this type. This is a matter of considerable practical importance which cannot be overlooked, every step towards lowering the interference level being of value.

It is clear from the above investigations that lack of attention to the adjustments of the spark injector unit can result in unsatisfactory welding, these adjustments being apart from the question of the phasing of the spark group dealt with earlier in the report. In the next section, the analysis of effects of the typical operation of the high frequency injector unit is carried a stage further.

It should again be noted that in the above work, the injector unit was a commercial pattern, with copper sparking electrodes. The question of what improvements in operation might accrue from attention to surface condition or electrode material, etc., is not, therefore, pursued here. Some such considerations, however, for spark gaps of this general type are dealt with in a paper* on the controlled spectrographic spark source.

6.3 Analysis of the Output with Reference to Phasing

The output of the injector unit has already been seen to take the form of groups of sparks separated by "dead" periods in which no sparks occur. The regularity of this train of events is now considered in relation to some arbitrarily selected but regularly repeating time zero. In Fig. 10 (*a*) and (*b*) the chain dashed line

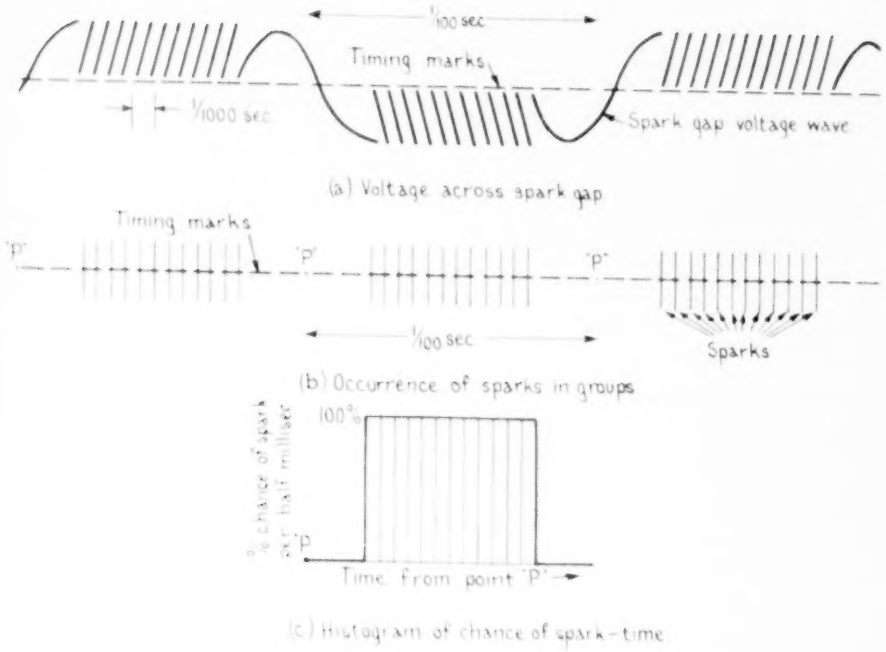
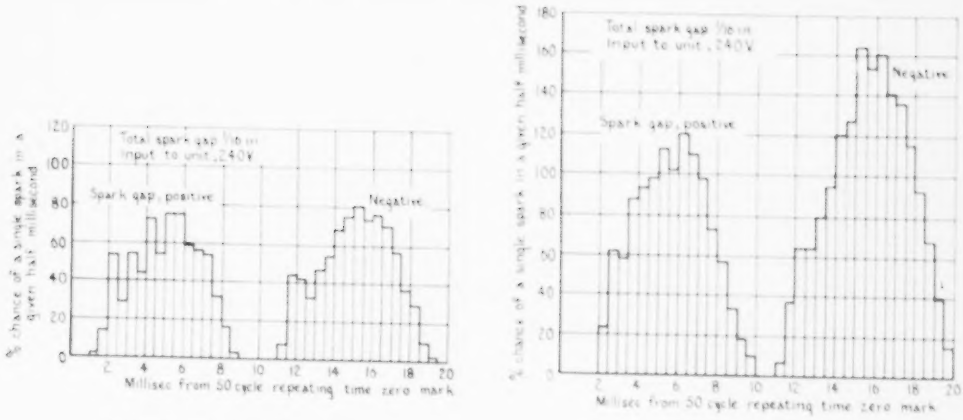


Fig. 10. Idealised form of H.F. injector output

represents a time calibration locked to mains frequency, the standard gaps in the line being at millisecond intervals, with larger gaps at 10 millisecond intervals. The spark gap voltage waveform of an idealised injector unit is sketched in Fig. 10 (*a*) with the sparks (represented by vertical dashes in Fig. 10 (*b*)) occurring in groups at regular intervals of time, also dependent on mains frequency. The leading spark of a given group, therefore, occurs at a fixed time in relation to some point, such as "P" selected on the timing scale. For convenience let "P" be at one of the 10 millisecond time marks.

Consider now the chance of a spark occurring in each half millisecond of time, measured from the arbitrary datum point "P." It is clear that immediately following "P," sparks are absent, so that the chance of occurrence is zero, and remains so until the leading spark of the group is approached, when, with sparks occurring in the group at a repetition frequency equal to one per half millisecond, the chance of occurrence becomes 100 per cent. A histogram of the chance of occurrence of a spark against time in half millisecond intervals from the arbitrary zero point "P" would appear as the sketch in Fig. 10 (*c*). This type of histogram suffers some modification in actual practice, and in Fig. 11 (*a*) a histogram is reproduced for a triple spark gap with all gaps operating normally. This histogram was derived from the cathode ray oscillogram by counting the number of sparks in each half millisecond interval for each of the 50 cycles (approximately) recorded. Due to the variations in actual operation it is seen that the chance of a spark occurring in a given half millisecond period does not change abruptly from zero to a maximum, but that the transition is more gradual, nor is the histogram flat topped over the spark group range.

It is clear that the effect of shifting the phase of the spark group relative to the welding current may be simulated by considering the effect of shifting the current zero along the time axis of the histogram. Assume that arc initiation is occasioned by spark injection only and that the first spark injected after current zero always results in breakdown to arcing conditions. Then if current zero is made to fall somewhere around the five millisecond point on the time axis of the histogram in Fig. 11 (*a*), it is clear that the chance of a spark occurring in the following one-and-a-half milliseconds is very high, i.e., the chance of "early" half cycle breakdown is very high. As, however, the current zero position is moved further along the time axis the chances of a spark occurring in succeeding half millisecond periods decreases fairly rapidly, i.e., the chance of "early" half cycle breakdown also decreases rapidly. With current zero falling still further along the time axis, the chance of a spark before the "dead" period is almost nil, i.e., the chance of "early" half cycle breakdown is also almost nil. Following this period the chance of a spark within a given time period begins to increase again until the 100 per cent. chance condition is again reached. Such a curve of "early" sparks (i.e., within a 1·5 millisecond period), against time (phase) is shown in Fig. 12 (*a*), on the same time scale as, and derived from the mean of the two sections of, the histogram in Fig. 11 (*a*). The appropriate phase shifts, in degrees which in this case would correspond with the millisecond time scale in Fig. 12 (*a*), have also been included. It is apparent that the form of this curve is the same as, for example, curve A of Fig. 5 (*a*) which shows the percentage number of half cycles in which breakdown to arcing conditions occurred "early," plotted against the phase displacement between the inputs of the spark unit and the welding transformer. In effect, Fig. 12 (*a*) is a curve


Total spark gap 1/16 in
Input to unit, 240V
Spark gap, positive
Negative
% chance of a single spark in a given half millisecond
Millisec from 50 cycle repeating time zero mark

(a) Triple gap—normal operation.

(b) Triple gap—one gap "misfiring."

Fig. 11. Histograms for triple spark gaps.

Table

No. of Spark Gaps in Series	Total Gap Width, inches	Input Voltage to Unit, r.m.s. Volts	Apparent Spark Gap Operation	Spark Gap Breakdown Potentials			No. of Half Cycles with Spark Gap "Conducting," per cent.	Average Number (and Standard Deviation) of Sparks per Group or Half Cycle		Fig. No. (if reproduced)
				Approximate Main Breakdown Volts		Approximate Quantity and Range of Additional Breakdowns, kV				
				Negative kV	Positive kV			Negative	Positive	
One	1/32	240	Abnormal (from record)	2·2	2·2	Many 0·7-1·7	50-60	†	†	9(a)
One	1/16	240	Abnormal (from record)	3·7	3·5	Many 0·8-1·6 and 2·1-3·3	25-30	10·4 (3·1)	11·2 (3·9)	9(b)
One	1/10	240	Crackling sound rather than hissing	4·5	—	None	None	1	0	—
One	1/12	240	Slightly abnormal (from record)	3·9	4·3	Some 1·4-2·6	Less than 5	8·1 (1·8)	7·6 (1·9)	
One	1/32	120	Normal	2·1	2·1	None	None	8·6 (1·9)	8·8 (1·5)	9(c)
Three	1/16	240	All gaps normal	3·8	4·1	Very few 2·7-3·5	None	8·0 (1·5)	6·9 (1·4)	9(d)
Three	1/16	240	One gap "misfiring"‡	2·9	3·5	Few 1·7-2·8	None	16·8 (2·9)	11·6 (2·8)	9(e)
Three	1/16	240	Two gaps "misfiring"‡	2·1	2·4	Few 1·2-1·6	None	27·4 (2·8)	22·3 (2·9)	9(f)

* Formation of a low voltage discharge lasting for the order of milliseconds.

† Spark gap operation too erratic for analysis.

‡ Discharges appear from a fixed point on the "misfiring" spark gap electrode, instead of at random.

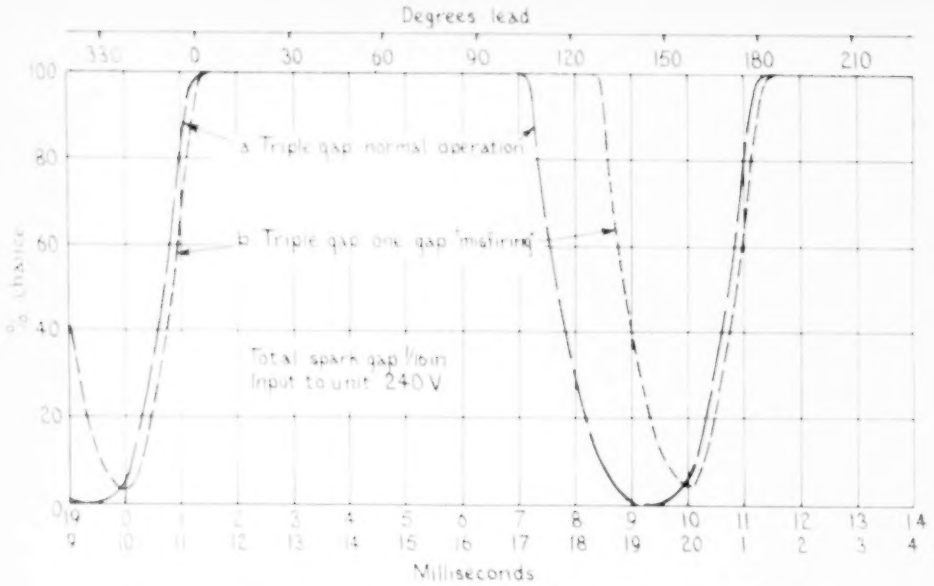


Fig. 12. Percentage chance of an "early" spark-time (phase). (Derived from Fig. 11(a) and (b).)

similar to A in Fig. 5, but unmodified by factors such as the failure of the arc gap to re-ignite on the first spark after current zero.

Other modes of spark gap operation may result in modified histograms, e.g., Figs. 11 (*a*) and 11 (*b*) are both constructed for a triple spark gap, but in the latter figure one gap was misfiring, the form of the resultant histogram being more "peaked" than in the former. A chance, greater than 100 per cent., of the occurrence of a single spark, as shown in Fig. 11 (*b*), implies that the repetition frequency of the sparks in a group has increased to something greater than one per half millisecond. The corresponding curves of "early breakdown" versus phase are thus modified in detail, but not in overall shape. (Compare Figs. 12 (*a*) and 12 (*b*).) Examination of such derived curves for a number of different operational conditions of the spark gap unit shows that their general overall characteristics, bearing on the phasing of the spark group relative to the welding current are:

(i) A broad region of high chance and a narrower region of low chance of "early" arc re-ignition.

(ii) A rapid transition from one region to the other in a phase shift of the order of 20 deg. (i.e., a millisecond).

(iii) That a change in the functioning of the spark gap can shift the transition from high to low chance of "early" arc re-ignition by the order of 20 deg. (a millisecond), whereas the reverse transition remains comparatively unaffected.

The extreme cases of spark gap operation to which the above analysis can be applied are firstly, if the injector unit was a source of a steady and continuous train of h.f. sparks, i.e., regularly repeating, at short time intervals such as could be obtained using a stable high voltage d.c. charging source, and secondly if it produced only a single spark per half cycle. In the former case the histogram would be a continuous flat-topped table or block, and the chance of "early" half cycle breakdown would remain at a maximum, whilst in the latter case it would consist of a single narrow block. It is obvious from general considerations that in the second example, phasing of the spark injection relative to the welding current would be critical for "early" breakdown, though such an arrangement would reduce the level of radio interference.

7. ADJUSTMENT FOR OPTIMUM PHASING OF THE INJECTOR UNIT IN PRACTICE

For a spark gap oscillator fed with high voltage alternating current as in typical commercial units, the minimum time between successive sparks occurs in general in the middle of the spark group, i.e., approximately in the middle of each half cycle. (See Fig. 9 (*d*).)

Assuming that the spark from the injector unit is the means of arc re-ignition in the welding circuit, then the spark oscillator must be about halfway through its group of sparks when the current in the welding circuit reaches zero, if the delay to arc re-ignition (current zero phase) is to be reduced to a minimum. The output from the injector unit should, therefore, lead the current in the welding circuit by about 90 deg.

In practice it appears preferable for the spark injection to lead the current by somewhat less than a full 90 deg., so that the middle of the spark group occurs just after welding current zero. This is because (i) it is possible that the first available spark may fail to cause arc re-ignition, a further spark or sparks being required, (ii) erratic behaviour of the spark gap, or even its sudden failure to operate at all, as can occur in a single gap, usually develops in the later half of the spark group (see Fig. 9 (*a*) and discussion in Section (6.2)), (iii) if for some reason the number of sparks in a group is low and more than a single spark is required to cause re-ignition, the end of the spark group may be reached before the welding arc has restruck. There is then a long period of delay (over the "dead" period) to the first spark in the succeeding spark group of the next half cycle, resulting in late half cycle breakdown or even rectification.

Due to circuit reactance, etc., the outputs of both the welding circuit, and the spark oscillator circuit have phase shifts relative to their inputs. Without measurement, therefore, it is not possible to state the phase relationship between the spark group and the welding current merely from the relative phases of their input supplies. In the present investigations this phase relationship for optimum operating conditions was determined experimentally by incorporating a phase shifting transformer in the input circuit of the injector unit.

Vector connection		AB	BC	CA	BA	CB	AC	AN	BN	CN	NA	NB	NC
Phase of above relative to BC	Lead	120	0	240	300	180	60	90	330	210	270	150	30
	Lag	240	360	120	60	180	300	270	30	150	90	210	330
Phase of above relative to AN	Lead	30	270	150	210	90	330	0	240	120	180	60	300
	Lag	330	90	210	150	270	30	360	120	240	180	300	60

Fig. 13. Vector diagram of 3-phase supply and star point (neutral)

Switch Position	Phase of Tapping relative to Lines BC	Voltage of Tapping
1	0	415
2	30	240
3	60	415
4	90	240
5	120	415
6	150	240

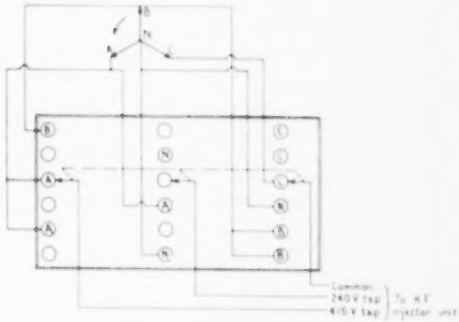


Fig. 14. Diagram of phase shifting switch.

In practice a sufficiently accurate series of phase displacements should be obtainable from the variations that can be made in the connections to the input of the injector unit from the mains three-phase and neutral supply. The relative phase between any pair of connections and one other reference pair can be varied in steps of 30 deg. from 0 deg. to 360 deg., as may be seen by reference to the vector diagram in Fig. 13 and the tabulated set of phase displacements with reference to the vector BC and the vector AN. It should be noted that both line to line (415 V.) and line to neutral (240 V.) voltages are involved so that the mains transformer of the high frequency spark unit should be provided with these two voltage tappings.

It has been stated in Section (5) above that in this work arc re-ignition appears uninfluenced to any marked extent by the spark half cycle polarity, i.e. uninfluenced by a phase shift of 180 deg. Hence, phase settings between 0 deg. and 180 deg. are regarded as equivalent to corresponding phase settings between 180 deg. and 360 deg. Thus, only half the number of possible connections listed in Fig. 13 need be investigated. Phase shifts from 0 deg. to 180 deg. in 30 deg. steps may easily be obtained using a simple three-pole, six-way switch, such as shown diagrammatically in Fig. 14. The tabulated data in this figure gives the switch positions and the resulting phase of the various tappings, assuming, for this illustrative case, connection of the welding transformer to BC.

With such a switch in the input circuit to the injector unit, switch positions should readily be found for satisfactory and unsatisfactory spark group phasing, for any given welding set up. From the broad topped nature of curve A in Fig. 5 it is likely that a series of several consecutive switch positions will be found giving reasonably satisfactory welding operation. By selecting a setting mid-way in this series, a close approximation should be obtained to the optimum phase relationship between the spark group from the injector unit and the current in the power welding circuit.

8. CONCLUSIONS

1. In any welding process utilising a high frequency spark oscillator for arc maintenance, such as in a.c. Argon arc welding of aluminium, the nature of the output of typical commercial spark injector units is such that it is essential for satisfactory welding that the input to the h.f. unit should be correctly phased relative to the power supply to the welding transformer.

2. The electromagnetic and cathode ray oscillograms obtained in the present investigations show the value of such recording as a means of analysing in detail the electrical parameters in the a.c. Argon arc process for welding aluminium.

3. The output of the commercial spark unit used in these tests consists of a group of individual sparks in every half cycle, each group being separated from the next by a "dead" period, in which sparks are absent. The time duration of these several phenomena were of the order of microseconds for individual sparks, a millisecond for the interval between individual sparks, 6 milliseconds for the spark group, and 4 milliseconds for the "dead" period between successive spark groups.

4. Phasing of the spark group, relative to the welding current such that the "dead" period falls around current zero, is clearly ineffective in initiating early arc re-ignition in the succeedinge half cycle. In practice it was found that the optimum relative phasing was such that the middle of the spark group occurred just after the welding current reached zero.

5. In these tests, in the absence of h.f. injection the arc extinguished for the reverse polarity half cycles (aluminium work piece negative). By adjustment of the phase of the injected spark groups relative to welding current, breakdown to arcing conditions could be made to occur either generally "early" or generally "late" in the reverse polarity half cycle, to fail altogether, or to exhibit in a given test a combination of these several classes of breakdown (arc re-ignition has been classed "early" if occurring within 1·5 milliseconds of current zero, and "late" if in excess of this time).

6. The most suitable phase positions for spark group injection result in early half cycle breakdown to arcing conditions. Under these conditions the melt run made on an Al-5%Mg alloy work plate without a filler rod was narrow and continuous. With injection resulting in both early and late half cycle breakdowns together with rectifications, the appearance of the run was roughened and irregular, whilst in the phase position resulting in the reverse polarity half cycles all breaking down late to arcing conditions, the run was surface "pitted." Except when arc re-ignition was regular and "early," the arc progressed along the work place in a series of small jumps. When there was marked variation in the time of zero pause (up to and including complete half cycle rectification), both the light output from the arc, and the sound output from the welding transformer fluctuated.

7. Apart from any question of radio interference, the simple and robust type of spark injector considered here, if correctly used and adjusted, appears to answer satisfactorily the requirements of this welding process.

8. In the present tests the surface condition of the work plate influenced results. Such differences were detectable, for example, between a scratch brushed surface of an Al-5%Mg alloy work piece, and one merely degreased before use. These differences did not indicate any major change in the best and worst phase positions for spark group injection, but modification in the shape of the curve relating early half cycle re-ignition to spark group phase position.

9. Differences were evident as between the alloy and a work piece of commercially pure aluminium. Under the conditions of test the difference was most evident in the tendency of a spark, even in a well-phased spark group, to fail to cause arc re-ignition with the aluminium. This implies that in practice some change in test conditions would be needed, such, for example, as a limited increase in open circuit welding voltage, change in current or variation in rate of argon flow, etc., to make the experimental set-up as suitable for work on commercially pure aluminium as on the alloy.

10. Even with conditions such that arc re-ignition regularly occurs with negligible time delay every half cycle, a current asymmetry exists for the tungsten-aluminium arc, i.e., a mean d.c. component is present unless steps are taken to prevent it. Further to this effect, additional current asymmetry is caused by the delayed breakdown to arcing conditions that can occur in half cycles of reverse polarity by varying the phase relationship between the injected spark group and the welding current. In these investigations, the reverse polarity current decreases by about 30 per cent. per millisecond delay from current zero to arc re-ignition (current zero pause).

11. Operational adjustments of the spark injector unit, both in applied voltage and in gap settings, etc., affect its performance, and these effects are reflected in its efficiency in promoting satisfactory welding. Although in the present work, investigation of such aspects was limited, a triple spark gap in the injector unit was, in general, found to be more satisfactory than a single gap.

12. The low open circuit voltage of 60 V. r.m.s. was chosen here so that, without h.f. spark injection, half cycle rectification would be encountered. Correct phasing of the injected spark group for the Al-5%Mg alloy eliminated both late half cycle breakdown to arcing conditions and rectification. It would appear possible, therefore, that careful attention to spark group phasing might permit a lowering of open circuit welding voltage in practice. More detailed investigation of this for other materials and test conditions is still required before this aspect can be pursued.

13. Optimum phasing of the injected spark group should be attainable in practice by incorporating a simple three-pole six-way switch in the input to the injector unit. Such a switch, connected to the three-phase and neutral supply, provides phase shifts in steps of 30 deg. from 0 deg. to 180 deg. and permits the most effective phase position for spark group injection to be determined experimentally.

9. ACKNOWLEDGMENTS

Thanks are expressed to Mr. P. Lale for his assistance in the experimental work.

The authors are indebted to the Director of the British Electrical and Allied Industries Research Association (E.R.A.) for permission to publish this paper.

LIST OF REFERENCES

1. Sellhant, R. R., and Woollcott, W. A. "The Argonarc Welding Process," *Welding*, vol. 17 (10), pp. 430-441 (Oct. 1949).

2. Orton, L. H., and Needham, J. C. "Short Time Phenomena in the Iron Welding Arc. Metal Bridging and Short Circuiting of the Arc," *Transactions Institute Welding*, vol. 12 (1); *Welding Research*, pp. 17r-24r (Feb. 1949) (based on E.R.A. Ref. Z/T73).

3. Orton, L. H., and Needham, J. C. "Microsecond Phenomena in the Steel Welding Arc." E.R.A. published report, Ref. Z/T79 (Sept. 1949).

4. Piper, T. E. "The Heliarc Welding Process as Applied in the Aircraft Industry," *Welding Journal*, vol. 24 (10), pp. 903-906 (Oct. 1945).

5. Welch, A. U. "Power Supply for Inert-Arc Welding," *ibid*, vol. 27 (5), pp. 376-378 (May 1948).

6. Herbst, H. T. "Electrical Characteristics of the Arc in Heliarc Welding," *ibid*, vol. 27 (8), pp. 600-604 (Aug. 1948).

7. Gibson, G. J., and Rothschild, G. R. "The Effect of D.C. Component in A.C. Inert-Gas Arc Welding of Aluminium," *ibid*, vol. 27 (10), *Research* Supplement, pp. 496s-501s (Oct. 1948).

8. Symposium on Spectroscopic Light Sources. A.S.T.M. Special Technical Publication No. 76 (1948), especially Enns, J. H., and Wolfe, R.A. "A Study of the Controlled Spectrographic Spark Source," pp. 12-18.

Printed in England by Lawrence Press Ltd., Henry Road, New Barnet, Herts